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A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

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PUBLISHED BY
THE AMERICAN PHYSICAL SOCIETY
LANCASTER, PA., AND ITHACA, N. Y.

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THE

PHYSICAL REVIEW.

ON THE VARIATIONS OF THE PHOTO-ELECTRIC CURRENT DUE TO HEATING AND THE OCCLUSION AND EMISSION OF GASES.

By L. A. Welo.

Introduction.

NEARLY all who have worked on the photo-electric effect have been aware of the strong influence of the surface conditions of the metal or of the effect of impurities which may be distributed throughout the body of the specimen under investigation. They have, however, concerned themselves only with the fullest possible elimination of these surface conditions or impurities by heating or scraping in high vacua; and, as far as the writer is aware, none have attempted to follow the course of the photo-sensitiveness at the various stages of cleaning until some measurements were made by Piersol[1] in this laboratory in 1916.

In addition to reporting on the changes in photo-sensitiveness of the cold metal after having been subjected to various degrees of heating in highly exhausted tubes, he shows that for palladium, at least, the amount of gas driven off is also large in intervals of high photo-sensitiveness and that the curve showing pressure change with heating current through the strip of metal closely parallels the heating current-photo current curve. The intimation is plain that different gases come off at different heating currents, and that the photo-electric current is affected by their kind.

It was this possibility that gave rise to the present investigation. Its immediate object was to examine, spectroscopically, the gases emitted by metals at different degrees of heating and to make the corresponding measurements of the photo-electric current after the metal had been allowed to cool to room temperature.

The Apparatus and the Experimental Procedure.

The simple apparatus shown in Fig. 1 consists really of two parts; the photo-electric cell proper and the Plücker tube for the examination

[1] Phys. Rev., 8, 238, 1916.

of the gases. An essential feature is the total small free space (about 4 c.c.) attained by using tubing only slightly larger than the mounting shown hatched in the figure. This mounting is a piece of porcelain tubing pierced by two heavy copper leads. The leads have pieces of

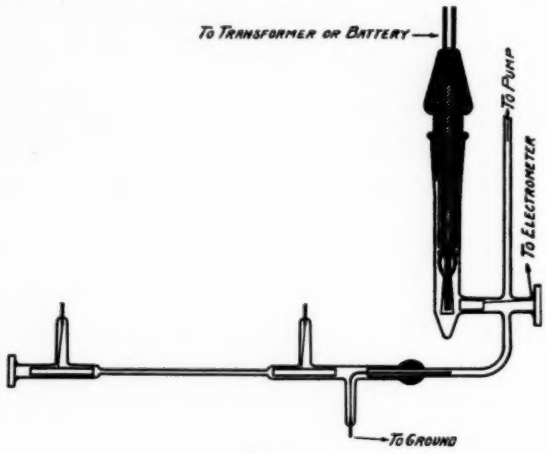


Fig. 1.

spring brass attached at the lower ends, pressing against the tongue formed by grinding away a part of the porcelain. The thin strips of metal of dimensions 6 × 38 mm. are bent to form a U and the ends slipped under the brass pieces. When thus mounted, the total radiation from the quartz mercury arc entering from the right and passing the cylindrical anode does not strike the middle of the strip. That the part subjected to radiation is of sensibly the same temperature as the middle is proven in that the strips fused above the corners of the U quite as often as between them. The ground joint at the top makes renewal of the metal strips easy. The parts of the apparatus that cannot be fused are joined with De Khotinsky cement.

Spectroscopic observations were made with both a small quartz spectrograph and a direct-vision instrument. The electrode marked "to ground" was in contact with some fine wires nearly filling the capillary joining the parts of the apparatus. The idea was that they might shield the cell from the discharge taking place while spectrograms were being taken. A deteriorating influence on the photo-electric behavior was sometimes noted unless this precaution was taken. The photo-currents, which were all within the range 1.6×10^{-12} and 1.0×10^{-10} amperes, were measured by the rate-of-charging method with a Dolezalek electrometer of sensibility of 50 divisions per volt. All of them are saturation values insured by joining one of the copper leads to the nega-

tive pole at a 100-volt battery, the other pole being earthed. When the strip was to be heated the battery connection was broken and the copper leads attached to a stepdown transformer with choke coil control. A transformer also produced the discharge in the Plücker tube.

A Gaede mercury rotary pump produced vacua so high that the discharge failed to pass through the Plücker tube with a 12 cm. spark gap in parallel, after the strip had been heated to high temperatures. Before so treated, gases are continually being emitted at ordinary temperatures and pressures less than 0.002 mm., gauge measure, cannot be obtained. During a part of the time mercury vapor was kept out with liquid air or absorbing alloys. Its presence is, apparently, without influence on the photo-electric effect. Except when gas was actually being driven off and tested the cell was always in communication with P_2O_5. In common with others who have done spectroscopic work with vacuum tubes at very low pressures, it was found impossible to get entirely rid of the lines and bands of traces of carbon compounds, cyanogen and water vapor. That such high vacua can be obtained after thorough heating of the strips shows that these traces come largely from the strip itself and not from the glass or De Khotinsky cement nor from the stopcock grease. At any rate there is no danger of confusing these traces of impurities with the very copious supplies of gas emitted by the metals at certain heating currents.

The usual experimental procedure is as follows: The pump connection is closed and the heating current sent through for eight periods of 25 seconds each. The spectrograms are then taken and notes made during the while of what is seen in the direct vision instrument. The gas is pumped out and by this time the metal has cooled nearly to room temperature, permitting two measurements of the photo-electric current. The metal is again heated with pump going and on cooling two new measurements are made. Following the second heating of four 25-second periods the photo-current is usually in agreement with that after the first to within 5 per cent. If it is not, there is alternate heating and measurements, after cooling, until two successive currents agree satisfactorily. At low heating currents the eight 25-second periods can as well be combined into one or two such that the total time of heating is 200 seconds. If enough gas is obtained on two or three heatings it may be examined and the pump run during the remainder of the 200 seconds of heating.

The Results.

The results of the photo-electric measurements are concisely presented in the curves. The last heating current is that at which the metal fused

so that the entire range of available temperatures is covered. The brackets above the curves summarize the changes in the gases emitted. "None" indicates that under the brackets so labelled there was either no gas emitted or there was not enough to permit the discharge to pass. The brackets labelled "hydrogen" need no explanation. Those marked "carbon" cover four possibilities. The carbon spectrum is given by CO_2, CO, some of the hydrocarbons and, as is well known, also by tubes filled with oxygen if carbon is present in some form; unless the supply is continually replaced by a fresh one, displacing the oxide formed with the carbon impurities on the glass, electrodes, etc., under the influence of the discharge. To the extent, then, that these four gases are liable to give the same spectrum the identity of the gas or gases coming off in the region marked "carbon" is an open question. Obviously, the usefulness of the spectroscope for such studies as these is at an end. Chemical analyses of these minute quantities of gas should be possible by the methods of Ramsay, Mond and Shield[1] or those lately used by Langmuir.[2] The changes from one gas to another are, of course, gradual and not so abrupt and definite as the brackets indicate. The brackets are placed after a thorough study of the spectrograms and after comparison with the notes made while observing visually.

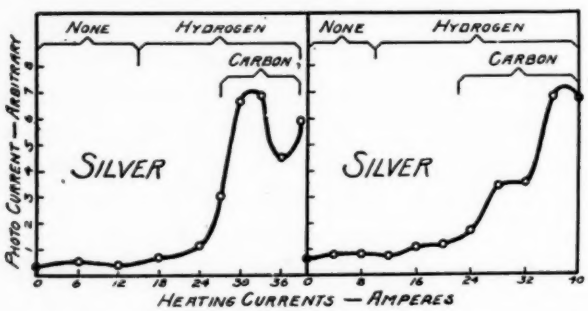


Fig. 2.

Fig. 2 shows what was obtained with two different pieces of silver The results of Piersol are verified; as the differences are not greater than those found among individual specimens. This metal shows a continual increase of photo-sensitiveness with increase of temperature (photo-currents measured after cooling) until a maximum is reached close to the fusion point. Beyond this a second maximum may begin to develop, as in the first sample, but usually the behavior is that of the second, where the metal fused while sensitiveness was on the decline. Hydrogen

[1] Phil. Trans. Roy. Soc., 186, 657, 1895.
[2] Amer. Chem. Soc. Jl., 34, 1310, 1912.

comes off at all heatings beyond the interval labelled "none" and for a time it is the only gas. When photo-sensitiveness begins to climb, carbon compounds or oxygen come off the sensitive metal and their spectra are the most prominent at heating currents giving also maximum photo-sensitiveness. Like hydrogen, the carbon gases continue to come until the metal is fused.

The next curve is for one of four pieces of gold. Two of the others were like that shown. The third differed in that after reaching a maximum, the photo-effect remained constant and unaffected by further heating. The results are the same as for silver except that the emission of the gases giving the carbon spectrum ceases and at the two last heatings only hydrogen is evolved.

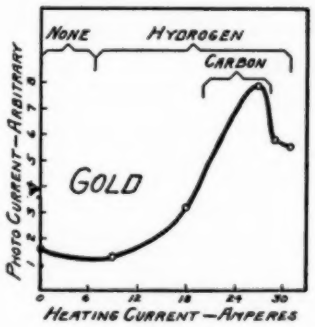


Fig. 3.

The spectra of the gases obtained from gold appear at the top of Plate I. The numbers at the right indicate the heating current used for driving off the gas giving the spectrum. The spectrograms are those for capacity in the discharge circuit. The lines may be identified on reference to the legend at the foot of the plate. It is noted that all of the carbon lines are strong with the gas driven off at 27 Å., which current also gives the maximum photo-electric effect. The hydrogen lines H_α

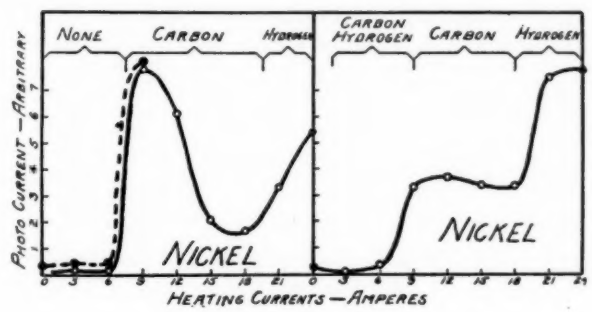


Fig. 4.

and H_β are out of the range of the spectrograph and with the small amounts of gas driven off from gold the less intense lines H_γ and H_δ could not be made to show on the photographs. Nearly all of what is being reported as to hydrogen is based on visual observations.

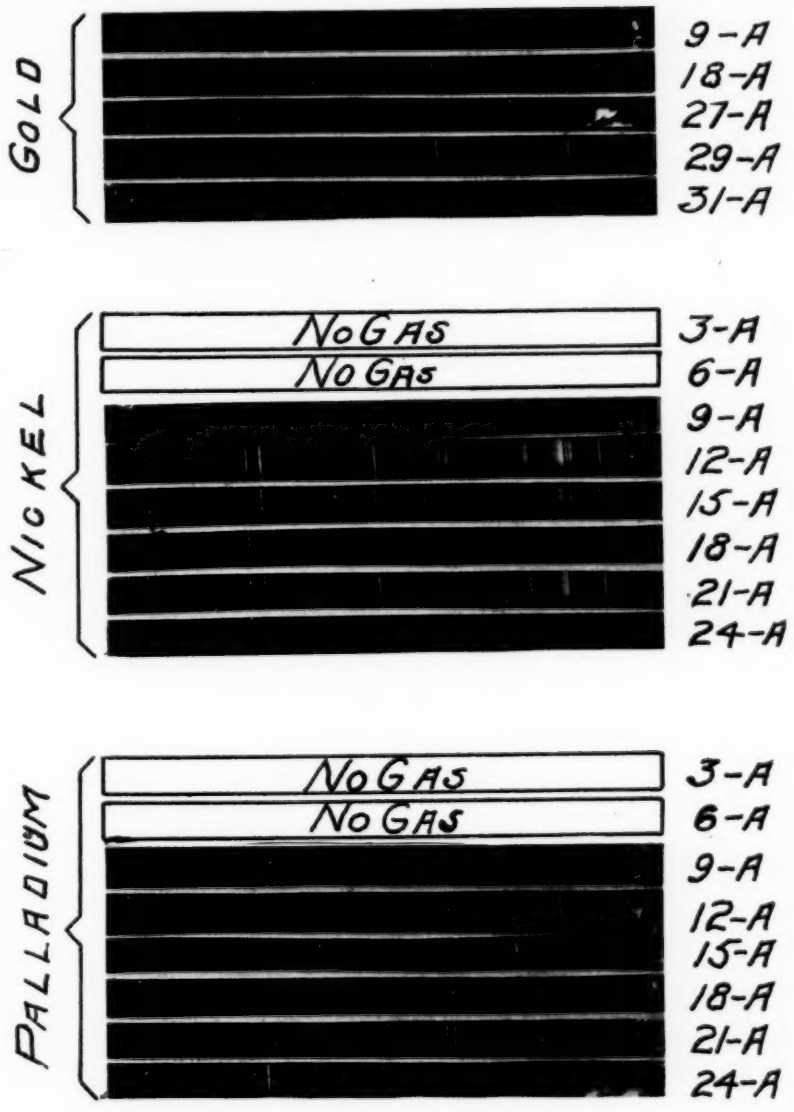
Three sets of data for nickel are presented in Fig. 4. The two curves which are complete illustrate the differences, with respect to both photo-sensitiveness and gas emission, that may be observed with different

specimens of the same metal. On the other hand, if two strips are cut from the same sheet of metal, the effects are reproducible as indicated by the dotted and solid curves at the left. The measured ordinates for the dotted curve were multiplied by the factor 0.61 to secure this fit. The curve was not completed because the cell sprung a leak while heating at 12 amperes. At first sight, the completed curves appear vastly different. Still the only difference seems to be that the depression present in the first at 15 and 18 amperes was not allowed to develop in the second, and that photo-sensitiveness remained unusually constant for four different heatings. They both show fairly constant sensitiveness at the beginning and a steep climb on approaching fusion.

The indications for the gases in the panel to the left refer to the curve shown solid. Like silver and gold, nickel also emits carbon gases or oxygen at the temperature which gives the first maximum in the heating current-photo current curve. Unlike silver and gold, the gases are not mixed with hydrogen but come off alone. Self-induction in the discharge circuit affords a delicate test for hydrogen in a mixture of gases. The test gave no hydrogen in the visible for the gases driven off with 9 and 12 amperes. Traces began to appear at 15 and 18 amperes, and at the fusing current of 24 amperes hydrogen alone was found. The differences noted at lower heating currents are due to the use of a smaller cell while taking the second set of data. In the first specimen the cell was too large to give good gas pressures with small heating currents. The gases are denoted as "none" because they could not be examined.

It is not exactly at the maximum of photo-sensitiveness that the carbon gases are alone or predominate but slightly beyond. The second curve shows this in that the first large value of the photo-current falls within the interval giving hydrogen and carbon. It is more forcibly brought out in the spectrograms which are to be taken in connection with the left-hand panel. At 9 amperes there are carbon lines, but they are more prominent at 12 amperes, in a region of descending photo-sensitiveness, and then become less and less intense relative to hydrogen. The last spectrogram shows a few faint carbon lines unavoidable in vacuum tube spectroscopy.

An interesting change in the appearance of the nickel may be noted. As it is obtained from the importers it is not shiny nor of a metallic luster as the other metals but looks like blue steel. The piece which was removed after heating at 12 amperes was white and had fully regained its luster. The large rise in the curves for nickel at 9 amperes is thus due to the removal of the visible deposit. Beyond 9 amperes for nickel, and


GOLD
9-A
18-A
27-A
29-A
31-A
NICKEL
NO GAS
NO GAS
3-A
6-A
9-A
12-A
15-A
18-A
21-A
24-A
PALLADIUM
NO GAS
NO GAS
3-A
6-A
9-A
12-A
15-A
18-A
21-A
24-A
C 2296
C 2478
C 2512
C 2836
C 2968
C 2994
C 3920
C 4266
Hg 2537
Hg 3132
H 4101
H 4341

L. A. WELO.

always with the other metals, the photo-electric changes are not accompanied by any visible changes of the surfaces.

The results for palladium, Fig. 5, are novel in that there are two narrow intervals in which carbon gases alone are emitted. Even self-induction in the circuit discloses no hydrogen. The carbon is not entirely absent in the interval marked "hydrogen" but the spectrograms for 15 and 18 amperes show carbon very faintly and in the visible region none at all is seen. At points just inside of the two maxima carbon is shown to be present in considerable quantities by the spectrograms for 12 and 21 amperes; but when one has a better basis for comparison, as in the visible where the hydrogen lines are strong, one sees that hydrogen is the principal gas where it is so indicated.

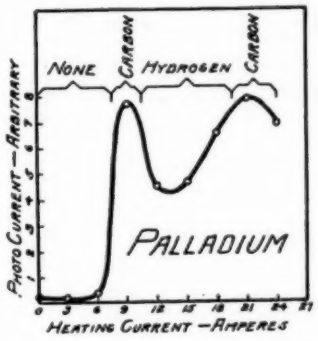


Fig. 5.

In the main, the two curves for the platinum of Fig. 6 agree. Only one principal maximum appears and at about the same heating current. The results for the gas analyses are identical. The spectrograms for this metal are not included. The very narrow peaks obtained by Piersol at 20 amperes on his scale of heating currents, and which should appear at about six here, were either missed or do not exist for this specimen.

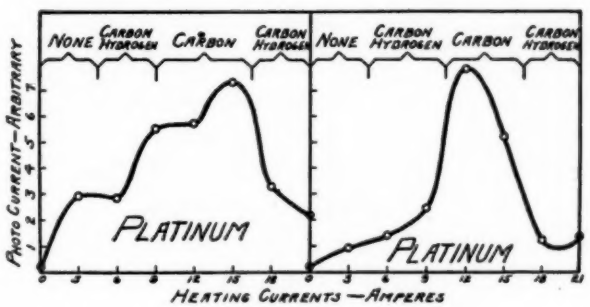


Fig. 6.

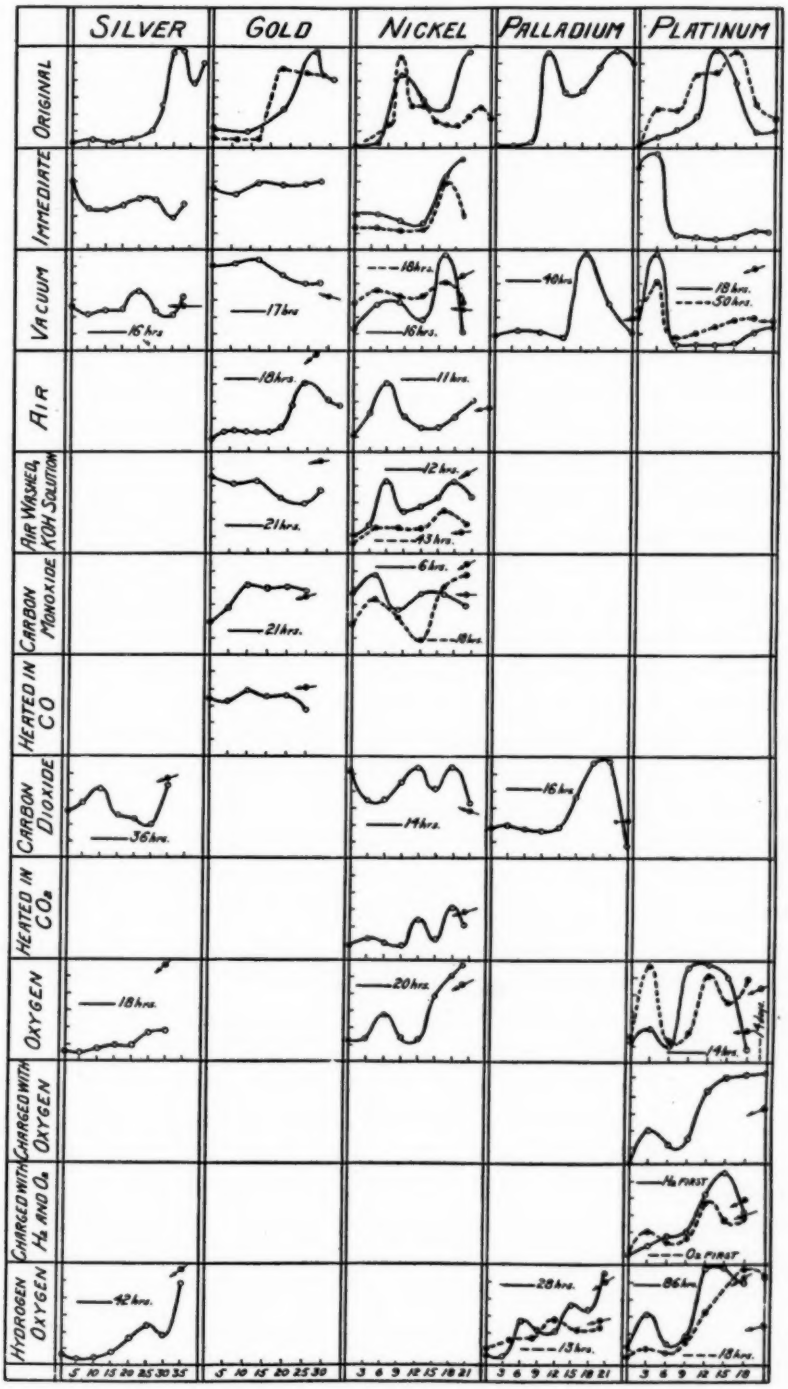
It is an interesting fact that if the point at the peak in Fig. 5 of his paper is disregarded, that curve will also show the two shelves on the ascending side. The gas analyses seem less definite with platinum than with the other metals. Hydrogen is never wholly absent, for in the intervals marked carbon the hydrogen spectrum is brought out with self-induction in the discharge circuit.

THE EFFECTS OF THE ADDED GASES.

On the completion of the tests which have been reported on in the preceding pages, it was thought that the work might most profitably be continued by treating the metals, cleaned by heating close to fusion in vacuum, with pure gases. The underlying idea was that it might be possible to imitate the original curves and identify more definitely the gases coming off as carbon compounds or oxygen. For this reason, most of the gases tried were hydrogen and those apt to give the carbon spectrum. Cyanogen was included because its bands are prominent among the impurities of the spectra. Nitrogen was expected to be without influence. The treatments accorded the metals were to let them stand, after cleaning, in the gas over night and sometimes even two weeks; or, to heat them in the gas close to fusion and gradually lower the temperature so a region of selective absorption should be passed through if one exists. A possible departure from the plan is to remove the metal from the cell, after heating, and charge it, electrolytically, with either hydrogen or oxygen or both. The photo-electric behavior of the metals after heating in plain or colored flames was also looked into with interesting results. The complete list of gases and conditions of treatment is contained in the columns at the left of Figs. 7 and 8. All of the gases, including air, were dried at least 24 hours over P_2O_5. As to their preparation and purification it is only necessary to say that Erdmann[1] was followed, except for nitrogen and hydrogen. Nitrogen was prepared by keeping air over a strong alkaline solution of pyrogallic acid. A similar solution also absorbed the oxygen gathered by diffusion by electrolytic hydrogen. No attempts were made to control the pressures while the gases surrounded the metals. The pressures were always high and anywhere from atmospheric to 30 cm. of mercury. Although the times of treatment with gas are indicated the use of them is made only in the discussion of results for palladium and platinum.

The scale of heating currents for each metal is given at the foot of each figure. Attention is called to the fact that each panel shows more than the variation of the photo-electric current with heat treatment. The constant photo-sensitiveness, obtained on sufficient heating at the cleaning temperature, is shown by the dot or ring through which the short arrow passes. The arrow is directed towards the point which measures photo-sensitiveness after treatment but before heating. Its slope is a rough measure of the rise, fall or constancy of photo-sensitiveness while the metal is being "gassed."

[1] Lehrbuch der Anorganischen Chemie.


SILVER
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NICKEL
PALLADIUM
PLATINUM
ORIGINAL
IMMEDIATE
VACUUM
AIR
AIR WASHED, KOH SOLUTION
CARBON MONOXIDE
HEATED IN CO
CARBON DIOXIDE
HEATED IN CO2
OXYGEN
CHARGED WITH OXYGEN
CHARGED WITH H2 AND O2
HYDROGEN OXYGEN
16 hrs.
36 hrs.
18 hrs.
42 hrs.
17 hrs.
21 hrs.
21 hrs.
18 hrs.
11 hrs.
12 hrs.
43 hrs.
6 hrs.
16 hrs.
14 hrs.
20 hrs.
40 hrs.
28 hrs.
13 hrs.
18 hrs.
50 hrs.
14 hrs.
H2 FIRST
O2 FIRST
86 hrs.
18 hrs.

Fig. 7.

All of the curves shown in solid lines in the row labelled "original" at the top of Fig. 7 will be recognized as some of those appearing in Figs. 2 to 6. Of the curves in the column for silver, those taken after treatment with hydrogen, oxygen or a mixture of the two, are the most illuminating. They illustrate one unusually good case of imitation of the original with the right combination of gases and how each produces its own independent effects.

It is seen that hydrogen does not lower the effect but raises it (arrow points upward slightly) and that the photo-effect is markedly constant until at the last heating current it is suddenly doubled. Oxygen, on the other hand, caused a drop from 104.5 to 10.6, and on heat treatment this sensitiveness is slowly trebled. In the mixture, the hydrogen has been able to bring about the sudden large increase on approaching the last heating current. At that point the oxygen which had the depressing and predominating influence on the sensitiveness is suddenly driven off as the spectroscopic data for the originals of Fig. 2 indicate, and the photo-current rises. If the oxygen were not so overpowering when it is present in silver the sensitiveness would certainly be higher in the interval of lower heating currents and would probably resemble the effects with hydrogen as to constancy also. If the comparison of the curve for mixed gases is made with the second curve of Fig. 2 it will be seen that both have a shelf or "kink" in the interval 28–32 amperes. It is not to be expected that the imitation should show the turn at the final heating because it is not at fusion, as is the original.

According to the information contained in the panel for carbon dioxide, this gas lowers the photo-electric effect but is far from being as disastrous as oxygen. Krüger and Taege[1] have examined the changes taking place when metals are surrounded by gas for short periods and report that with CO_2 the change is slight. The fall observed here is not slight. The truth seems to be that its influence is slight only when it is not the only gas present, as is not the case here.

It is further to be noted that the maximum at 10 amperes bears no relation to anything that is observed on the original, or the curve obtained after treatment with other gases. Carbon dioxide introduces features into cleaned nickel, also, which are observed nowhere else. As will presently be shown, it is without influence on even clean palladium. The view of the action of carbon dioxide which seems to be most consistent with what has been observed here and with published data is that it is without influence in the presence of other gases, such as oxygen and carbon monoxide. However, when these gases, including carbon dioxide,

[1] Zeit. Elekt. Chem., 21, 562, 1915.

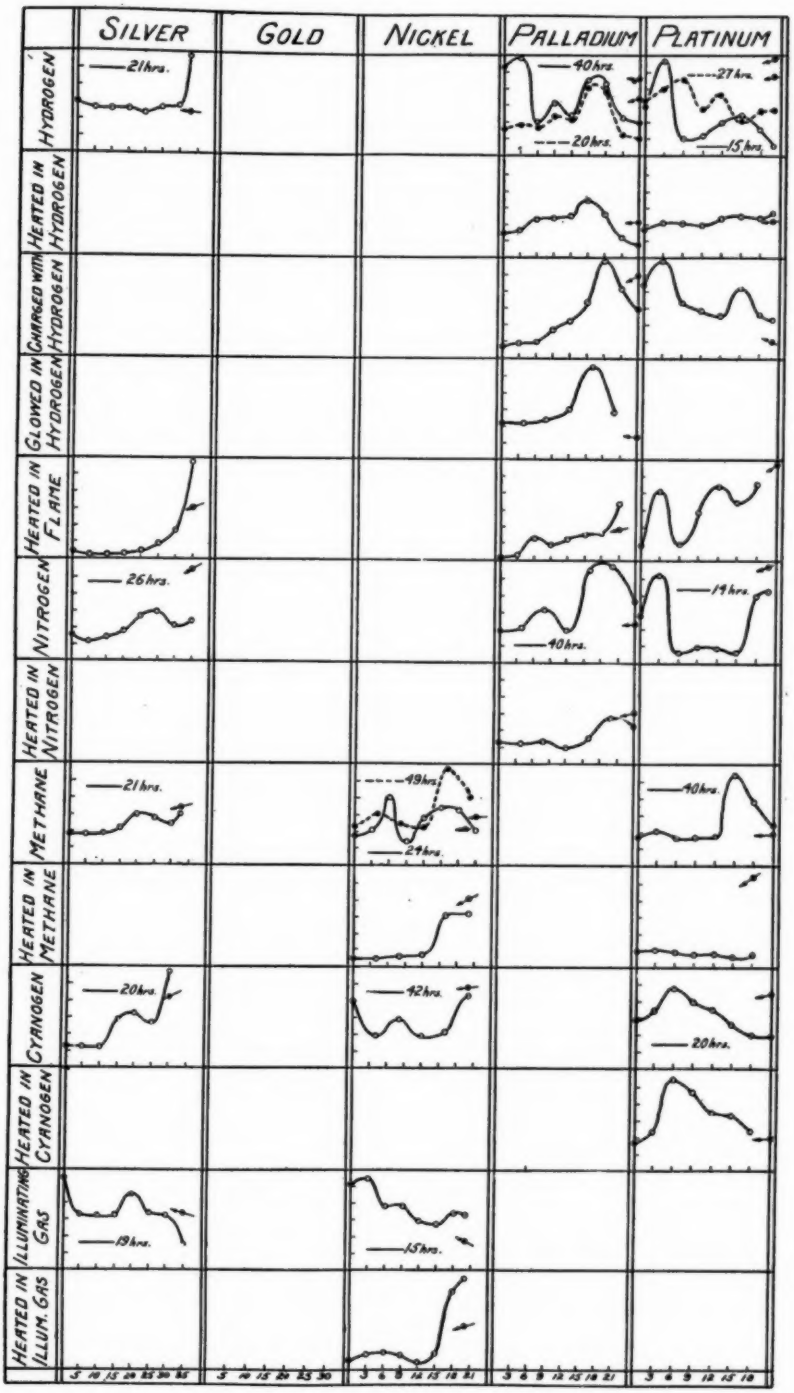
SILVER
GOLD
NICKEL
PALLADIUM
PLATINUM
HYDROGEN
HEATED IN HYDROGEN
CHARGED WITH HYDROGEN
GLOWED IN HYDROGEN
HEATED IN FLAME
NITROGEN
HEATED IN NITROGEN
METHANE
HEATED IN METHANE
CYANOGEN
HEATED IN CYANOGEN
ILLUMINATING GAS
HEATED IN ILLUM. GAS
21 hrs.
40 hrs.
20 hrs.
27 hrs.
15 hrs.
26 hrs.
40 hrs.
19 hrs.
21 hrs.
19 hrs.
21 hrs.
40 hrs.
20 hrs.
42 hrs.
20 hrs.
19 hrs.
15 hrs.

Fig. 8.

are removed by high heat in a vacuum and the carbon dioxide reintroduced a decreased photo-effect is observed with characteristic elevations and depressions in the heating current-photo current curves, of which there were no traces during the original cleaning.

When we are to make a decision as to the effects of the gases methane, cyanogen and nitrogen we need another basis of comparison than the original, for there is no similarity. This basis is gotten by going through a curve for a strip which has remained in a vacuum for several hours after cleaning; or better, one which has been gone through immediately. Such a curve is known as "immediate." The ordinate at zero amperes is really the ordinate which measures photo-sensitiveness after the strip has cooled from heating as close to fusion as possible. It is quite surprising that the variations should be so large and it is only with gold that anything like the expected constancy appears.

Let us turn for a moment from a discussion of the curves for silver and consider the effects of the gases experimented with on gold. It was thought at first that the curve for air gave the imitation of the original and that the active component was the carbon dioxide; for the curve is entirely different from that in the panel beneath. It has been shown, however, that CO_2 is inactive. The curve then does not illustrate the effect of the gas. It is included in the figure because it shows the existence of a lag between the emission of gas and the corresponding heating current and it shows also what happens when the cleaning is incomplete. What is to be noticed is that the gold was cleaned at 27 amperes and was fused after treatment at 33 amperes. In the vicinity of 27 amperes the curve is, after treatment, exactly like the original. The photo-current was not constant up to 27 amperes, as one would expect. The curve shows that the original cleaning at 27 amperes did not completely remove the gas which begins to come off then; although heating at 27 amperes was continued until constant photo-sensitiveness was attained. While most of a gas which begins to come off at a certain heating current is removed at that heating current it takes a higher temperature to remove the rest of the gas. A certain persistence shows itself. This view is in accord with what was seen in the Figs. 2 to 6. The heating currents at which gases showing carbon spectra first come off were quite definite but the same gases continued to come for two or three higher heating currents.

The immediate curve with gold shows an unusual constancy as compared with corresponding curves for the other metals. The depression at 6 amperes shows a slight fatigue. It should be remarked that it takes about 3 hours to obtain the data for a curve and that, with metals of such high electrical and heat conductivities as silver and gold, over an

hour may elapse before one is far enough along to give temperatures sufficiently high to counteract the fatigue, whatever its cause may be. With the other metals, the temperatures are high even at the first heating current and they glow at 6 amperes. The reason that gold does not show the large variations in the immediate curve is connected with its chemical inactivity as compared with silver and nickel and that it does not possess the property to any extent of absorbing gases.

The remaining curves for gold show the characteristic "corner" at 12 amperes beyond which the photo-effect falls. The oxygen of the air and the carbon monoxide affect gold similarly. The changes found in gold in vacuum are due to traces of either or both of these gases in the cell. Examination of these curves in connection with corresponding curves for nickel makes it appear highly probable that it is the carbon monoxide. The oxygen acting on nickel gives an excellent imitation of the original shown solid, which is the most frequent type. It shows the narrow maximum around 6 or 9 amperes.

The carbon monoxide, however, gives for both of the curves of the panel the broad maximum extending from 0 to 12 amperes, which is clear and definite for the solid curve for vacuum and which shows itself also in the dotted. It is well to call attention here to the irregularities at the ends of all the nickel curves. They are either ascending or descending as the metal fuses. The reason is that the second maximum for the original nickel curves appears so close to the fusion point. The maximum is narrow and never located at exactly the same place; so it may happen that one specimen will fuse before the peak is reached, while another fuses after the high photo-sensitiveness is passed. This, together with the lag and the persistence of the gases noted for gold, makes it impossible to attach any importance to the latter parts of the nickel curves. That the behavior at the ends for nickel is quite independent of the gases used in treatment is further shown, in that the ends with all gases are the same as the ends of one or the other of the originals. This may even be said of the curve for illuminating gas. Comparison of the nickel curves for oxygen and air seems to indicate that oxygen gives a narrow maximum at six amperes and not a broad one such as comes with carbon monoxide and vacuum. In the lower dotted curve for air a different set of points was taken, so that the elevation was probably missed. Provisionally, until we have examined the effects of methane, we can say that it is the residual carbon monoxide which gives rise to the irregularities derived in the vacuum.

Returning now to the discussion of silver we notice that the vacuum, nitrogen, methane and cyanogen give curves of the same type. The

photo-sensitiveness is constant until heating currents of 15 to 20 amperes are reached. Around 20 amperes there is an elevation followed by the normal rise on approaching fusion. The three gases mentioned have thus no effect on silver and are not even able to protect the specimen from the action of the residual gas. This gas is, provisionally, carbon monoxide; unless we are not dealing with the effects of a gas at all, but with some inherent impurity of the metal. This possibility will be considered in connection with the work on platinum.

The curve obtained with illuminating gas is an interesting one. The sharp maximum at 20 amperes is to be expected with any gas containing carbon monoxide. The rise in sensitiveness is unusual and is even more pronounced with nickel. The curve for the latter metal is very complex. The initial high value in both metals is due to some other gas than methane. Evidently it is easily driven from the silver, for beginning at 3 amperes, the photo-electric effect is constant until the elevation given by carbon monoxide is reached. Beyond this, there is constancy and then a sudden dip. One explanation of the fall is the presence of hydrogen sulphide. It was found by Krüger and Taege[1] that this and other catalytic poisons all lowered the photo-electric effect. It is necessary to assume, however, that the gas is driven off only with great difficulty and that the traces are active only when other gases have been removed. Small quantities may have been left on the walls of the cell. It could not have been on the silver, for the gas would have dissociated long before higher heating currents were used.

After silver, cleaned by heating in a vacuum, is further heated about a dozen times in a Bunsen flame, small irregularities are removed. Since cooling takes place in the oxygen of the air we find the small photo-sensitiveness at lower heating currents. If we had only the curves for silver to go by we should conclude that to imitate the originals it is only necessary to heat them as they were heated during the rolling; which, as the refiners state in a private letter, is with an air blast. Similar treatment of palladium and platinum fails to produce an imitation of any of the originals.

Although cyanogen and methane were not active on the silver the former affects the first reading on nickel and the latter gives curves of the same type as those for carbon monoxide. Although one of the methane curves shows a narrow maximum at 6 amperes the other is of the characteristic breadth. It becomes necessary to change our statement, made previously, that the effects introduced in the vacuum are due to carbon monoxide. It may be this gas or methane. In either

[1] Loc. cit.

case the statement holds that cyanogen and nitrogen are without influence on silver.

One must not think that the first maximum in the original of nickel is related to methane, although the gas gives good imitation. The spectrum of methane shows hydrogen largely, whereas the gas emitted while the original curve is being run through shows no hydrogen, even when the attempt is made to bring out its lines with self-induction in the circuit. This observation practically eliminates the possibility that a hydrocarbon is one of the gases driven off in the intervals marked "carbon" in Figs. 2 to 6. The carbon dioxide has already been shown to be without effect when other gases are present, so that there are left to be included under the "carbon" spectrum only oxygen and carbon monoxide. With silver it is certainly oxygen. With gold and nickel no decision can be made.

Another observation is not out of the way here. On one occasion the cell and Plücker tube were joined by a capillary bent in the form of a U. The pressure was decreased on the immersion of the capillary in liquid air but the spectrum was unchanged in character. Mixtures of gases are thus seen to come off at times.

The cyanogen has only affected the first part of the curve for nickel. After standing 42 hours, the nickel has been slightly reduced in sensitiveness. This condition is easily removed, for at the first heating current the photo-sensitiveness is reduced to one half. The sharp maximum at 9 amperes and the appearance of the end of the curve indicates the presence of oxygen. A trace of oxygen would also account for the fact that with silver in cyanogen the three first ordinates are lower than is silver in methane, nitrogen and vacuum.

The curve for nickel in illuminating gas is altogether too complex to follow, but the same cause which increases the sensitiveness of silver acts on nickel also. One thing worth noticing about the two curves for illuminating gas is this: the latter part of the silver curve fits the curve for nickel from 3 to 12 amperes. It is to be remembered that larger currents are necessary to produce a given temperature with silver and gold than with the other metals. It appears that if we were using temperatures instead of heating currents as abscissæ we should obtain with illuminating gas, and very often other gases, similar curves for the different metals.

Usually, when metals are heated in any gas there is a sharp decrease in photo-sensitiveness. Heating nickel in methane conforms to the rule, and the usual constancy with increase of the temperature is also noted. The unusual feature is the sudden rise at 15 amperes. As it appears

with methane it is to be expected with illuminating gas. The fall at the end of the curve for silver and noticeable also in nickel in illuminating gas does not appear after heating in the gas. The H_2S which probably caused it is decomposed as soon as the metal is heated above 310°.

We know from Fig. 4 that a gas giving the hydrogen spectrum comes from nickel at high heating currents. Methane and other hydrocarbons give this spectrum. There is a relation between this and the fact that after heating in methane and illuminating gas the high maxima, also appearing at the ends of the originals, are seen. Heating platinum in methane, on the other hand, gives a very constant photo-sensitiveness at all heating currents. A chemical analysis of the gases emitted on heating nickel would in all probability reveal, not only hydrogen in the intervals so labelled, but one or more hydrocarbons.

It is among the curves for palladium that we notice for the first time any influence of the time of standing in the gas. We see it in the palladium treated with hydrogen, oxygen and a mixture of the two. After palladium has been in the mixture for 13 hours it has developed a trace of irregularity and when the metal has stood for twice this time, two prominent maxima have appeared. They are nearly at the heating currents required for the imitation of the original curve for palladium. One reason why they are displaced to the left is that this specimen fused at 20 amperes instead of at 24 for the original. The effect of time is, however, even more noticeable with palladium in hydrogen. After standing for 20 hours, only, the last of the three maxima is fully developed. After 40 hours, two additional elevations barely traced before are fully developed and one of them to a very great extent. The maxima appearing in palladium at 15–18 amperes can be introduced into the curves by the hydrogen under all conditions of treatment and also by residual gases and vapors of the vacuum. It is more reasonable to think that carbon dioxide did not introduce the maxima but that this gas and the nitrogen failed to protect the palladium from the action of the residual gases. Perhaps hydrogen, too, is unable to give this protection. It seems that oxygen is essential in order to protect the metal from this action, for the maximum does not appear after heating in a flame: this process involving exposure to the oxygen of the air. The solid curve for hydrogen-oxygen indicates that even in the presence of oxygen, the elevation due to residual gases will develop if sufficient time is allowed.

Heating in hydrogen gives a different result from heating in any of the other gases; as there is a slight increase during heating instead of a very large fall in photo-sensitiveness. It is seen that on heating in hydrogen and nitrogen the shape of the curves obtained on merely

standing in the gas is preserved. Platinum when so heated shows afterwards only small variations. By heating platinum in hydrogen or methane more constant photo-currents can be obtained than in any other way. Charging palladium electrolytically, and making it the cathode in a glow discharge results in identical heating current-photo-current curves. A fall in sensitiveness is given during the first operation. The mere doubling of photo-sensitiveness seems small in the face of the results obtained in glowing the alkali metals, and those observed by Greinacher[1] on glowing with lead, zinc and platinum; but this is an isolated observation, whereas Greinacher's ratios (for platinum) vary from 1 to 100. The important thing here is that palladium thus treated gives the usual type of curve with hydrogen. The large drop when charging with hydrogen is due to the exposure to air during transfer to the electrolytic cell. Confinement in an atmosphere of hydrogen for 15 minutes before the transfer was tried as a means of preventing this action.

There is some good ground for the belief that nitrogen does affect palladium. There is also an elevation for palladium at 6 amperes on heating in the flame, involving contact with nitrogen during cooling. The sudden rise at the end of the platinum curve for this gas is surprising since the larger part of the curve is exactly like the immediate and vacuum curves for the same metal.

The high sensitiveness at 3 amperes and the unusual fall on going to 6 amperes is characteristic of nearly all the observations on platinum. The phenomenon can best be accounted for by the action of residual gases, since this feature is so marked in the curves for the vacuum. The appearance of the maximum in the immediate curve shows that the action is very rapid. The effect is undoubtedly connected with the observation made by Zeleny,[2] and subsequently by Davidson,[3] who studied the photo-effect of wires heated in air. A sudden dip took place in the temperature-photocurrent curves on passing through 100°. Zeleny believed the phenomenon due to properties of the metal itself but Davidson showed that it was due to occluded gases. It is well known that oxygen condenses on the surface of platinum, but the property does not depend on the temperature to any extent as compared with the property of palladium absorbing hydrogen at 100°. The curves already discussed have not indicated the presence of oxygen as a residual active gas and it is further seen that platinum must stand a long time in oxygen before

[1] Deutsch. Phys. Gesell. Ber., 15, 797, 1913.
[2] PHYS. REV., 12, 321, 1901.
[3] PHYS. REV., 26, 1, 1908.

the high photo-sensitiveness at 3 amperes shows itself. In fact, oxygen seems, with cyanogen, to be the only gas capable of suppressing the high sensibility. The other gases, such as hydrogen and nitrogen, fail to protect the metal. When oxygen is present it takes a long time for the residual gas to bring about its effects. For instance, when platinum had been in oxygen 14 hours, the peak at 3 amperes is not pronounced while after similar treatment of another specimen for 14 days the peak is 3 times as high. A growth in the same ratio occurs when treated for different times in a mixture of hydrogen and oxygen.

The pronounced sensitiveness at 3 amperes cannot be accounted for on the theory of Richardson[1] that there are impurities in the platinum, mainly sodium and potassium, which are driven to the surface on heating, or even evaporated. Sheard and Woodbury,[2] while confirming Richardson's views in the field of positive ionization from hot metals, use as a part of their argument, the time variation of the thermionic current at 725° just after heating to 800°. Here, however, no decay was noticeable. The photo-measurements made after the two heatings at 3 amperes, cooling and evacuations were in agreement within the experimental error. There is a further difficulty with the view that we are dealing with some easily vaporized metallic impurity in the platinum. No such maximum at 3 amperes, with fall on going to six, is noticeable in the original curves. The peaks observed by Piersol are farther along on the curves (at 6 amperes on the present scale of heating currents). The absence of the effect from the originals is easily accounted for on the theory of the action of residual gases. They are unable to attack the platinum as long as it is protected by the gases already on the new strips. A remark in Davidson's paper is of significance here. He tells of having raised the platinum to a bright red heat before going through the curve with the dip at 100 degrees, similar to that seen here in passing from 3 to 6 amperes of heating current.

In all of the curves involving the presence of oxygen alone, or as a part of a mixture, the maxima of the original curves at 12 or 15 amperes appear: wholly in accord with the belief that all of the maxima may be attributed to oxygen—unless it be carbon monoxide. The two curves for hydrogen are inconsistent. The solid one, however, is not of different type from that gotten by charging with hydrogen electrolytically. As with palladium, it is shown that the manner of treating with a given gas is indifferent. Heating in a gas is another matter.

Charging platinum electrolytically with oxygen destroys its activity

[1] Phil. Mag., 20, 545 and 981, 1910.

[2] PHYS. REV., 2, 288, 1913.

towards ultra-violet light. On heating, the activity is regained and follows the usual course for oxygen except at the end, where a high constant sensitivity is approached. It is worth mentioning that large quantities of gas were emitted at all heating currents beginning with 12 amperes, where photo-sensitiveness also is high for the first time. The curves in the panel marked "charged with H_2 and O_2" were taken after charging with both gases but in inverse orders. The time integrals of the charging currents are the same. The two curves bring out the fact that oxygen is the gas of predominating influence, even when the metal is so thoroughly treated with another gas as in the process of charging, electrolytically, with hydrogen.

The methane curve is interesting on account of the constancy until 15 amperes is reached. The effects of the residual gas have not been completely repressed because a small elevation shows itself at 3 amperes. The latter part of the curve is like the curve for hydrogen. The maxima at 15 amperes with platinum in hydrogen and methane are coincident with the maxima of the originals. As has been pointed out, there is a trace of hydrogen in the intervals of the original platinum curves marked "carbon" under proper conditions of the discharge. It is probable that with platinum, the maxima produced by more than one gas do coincide. Finally, leaving the curve for heating in flame to the next section, there remains only a consideration of the effects of cyanogen. The curves are of an entirely new kind. They are exceptional also in this: that heating in the gas gives the same type of curve as mere contact with gas and also does not lower the sensitiveness. The arrow has practically a zero slope.

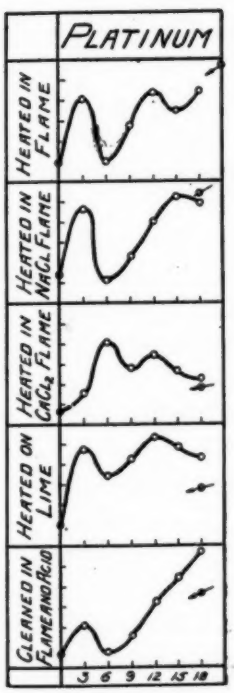

Fig. 9.

THE EFFECTS OF HEATING IN FLAMES.

Two considerations guided the work recorded in Fig. 9. One was the possibility of collecting easily ionizable active material from flames, plain or colored, and the other was that during manufacture the platinum was known to have been heated in the flames in lime crucibles. All five curves were taken with the same strip so that individual differences among specimens of platinum are eliminated. The flames raised the metal to a white heat. The heat was also white when the platinum was imbedded in pulverized lime.

As to the type, the upper two curves do not differ from curves obtained after treatment with oxygen. During treatment in an uncolored flame the sensitiveness fell in the ratio 6.25 while with heating in the sodium chloride flame this ratio was 3.9. The salt thus leaves an activity. It is easily removed and has no influence on the curve that follows, for in both curves the sensitiveness, in going from 3 to 6 amperes, falls in the ratio 4.1. The effect of the residual gas causing the high sensitiveness at 3 amperes is visible.

Heating in a flame colored with calcium chloride does give immunity against residual gas Heating on lime does not. A still more photo-active material is left by the calcium than by the sodium salt for the drop in sensitiveness is only 2.7 (for both lime treatments) instead of the 3.9 for sodium and 6.25 for the uncolored flame. It is at the higher heating currents that the effect of calcium shows itself best. From 12 amperes on, the two are alike and also similar to the original curves for platinum, although the decrease in photo-sensitiveness is not so rapid. It has occurred to the writer that calcium carbonate may be the cause of the variations observed in the original curves and that the carbon spectrum is given by the carbon dioxide released on the dissociation of the carbonate. No data have been found as to the photo-electric properties of the calcium oxide which would thus be left on the platinum but Debye[1] and Richardson[2] have shown, theoretically, that an intimate relation exists between electron emission at high temperature and by ultra-violet light. In view of the use of lime for the Wehnelt cathode its photo-electric activity might be high. It is well to keep in mind that the behavior after heating on lime is not due to something remaining from the heating in calcium chloride flame. The platinum was used in the meantime for three of the curves of Fig. 7, namely, hydrogen for 15 hours, and the two for the metal charged electrolytically with both hydrogen and oxygen.

Concordant results could not be obtained by Davidson[3] in his study of ionization phenomena, by mere heating in a flame. Cleaning was accomplished by alternate dipping in acid and heating in flame while the metal was charged to a high negative potential if the impurity to be removed was alkaline earth. This plan was followed here and the last curve of Fig. 9 resulted. There was no immunity to residual vapors, as the maximum at 3 amperes shows. The platinum has been entirely freed of those irregularities, characteristic after treatment in calcium

[1] Ann. d. Phys., 33, 441, 1910.
[2] Phil. Mag., 23, 263 and 594, 1912; 24, 570, 1912.
[3] Loc. cit.

or all of the gases. The only curve at all like it is that obtained on charging with oxygen electrolytically.

Some General Considerations and Suggestions for Further Experiments.

The experiments, the description of which forms the basis of this paper, are inadequate and our knowledge of the mechanism of occlusion and adsorption too meager to justify any theory of the variations at this stage. In this, the concluding section, then, a few of the possibilities will be considered and the means indicated of deciding among some of them.

A quite satisfactory theory of adsorption is that devised by Langmuir[1] and supported by his extensive studies of the electron emission and chemical reactions at low pressures and high temperatures, principally with tungsten and platinum. Taking the special case of oxygen adsorbed on tungsten: one single layer of oxygen atoms is joined to the surface layer of tungsten atoms because the two primary valences of oxygen are turned down and are saturated by the tungsten atoms. In the case of carbon monoxide, two of the four primary carbon valences are turned down and saturated by the tungsten so that the diagrammatic representation will consist of the surface layer of tungsten atoms, then a layer of carbon atoms, and finally, on top, a layer of oxygen atoms whose two primary valences are saturated by the two carbon valences turned upward. The nitrogen atoms are mutually very thoroughly saturated, so that this gas is held to a surface only by weak secondary forces and thus is not readily adsorbed. The important thing, in connection with the present subject, is that only one layer can be formed. The forces holding the possible second or third layers would be weak so that the number of atoms in these layers would be negligible. The extent of adsorption is, thus, determined by the area of metal covered with atoms of gas.

The elimination of the adsorbed layer by heating or other means is, then, to be looked upon as the formation of gaps in the surface layer and further cleaning merely as an increase in the areas of the patches of bare metal. Assuming that only the bare metal is photo-sensitive, the rise in the photo-electric current is also accounted for. The fall of the photo-current beyond the maximum can be explained by the formation, at particular temperatures and pressures, of a new layer of another gas. No observation has been made on platinum, but one for tungsten is reported on by Langmuir.[2] In speaking of the impossibility of dis-

[1] Amer. Chem. Soc. Jl., 38, 2221, 1916, and Phys. Rev., 8, 149, 1916.

[2] Amer. Chem. Soc. Jl., 38, 2272, 1916.

sociating hydrogen with an oxygen-covered filament or of causing chemical combination of the two gases, even at a temperature of 1200°, he says: "If, however, we assume that the oxygen atoms are chemically combined to the mass of the tungsten filament and forms a *continuous* surface layer, all of the observed facts are readily accounted for. The oxygen atoms are saturated chemically by the tungsten (primary valence) and the field of force holding the oxygen atoms lies wholly below the surface where the hydrogen molecules cannot reach it. When the pressure of oxygen falls so low that the supply of this gas at the surface is not sufficient to make up for the loss by evaporation, the gaps are formed in the continuous covering and the hydrogen is then able to make a *flank attack* on the oxygen. In this way the oxygen covering is *suddenly* removed when the pressure of oxygen falls below a certain critical value, and the dissociation of hydrogen, therefore, begins at once." The sudden removal of oxygen is significant in the light of the spectroscopic results in our original curves. Here is a case of the removal of one adsorbed layer facilitating the access and formation of a new one from residual vapors or gases. This layer causes a depression in the heating current-photo current curve until clean patches of metal begin to appear at higher temperatures. The removal of this second layer might facilitate the formation of a third layer bringing about the descent from the second maximum in the curve for palladium, Fig. 5. It would seem that a study of the photo-electric current from tungsten along the lines of the present paper might be undertaken with profit. In view of the extended experimental work of the last 6 years by Langmuir it is almost certain that more is known of the behavior of tungsten towards gases than of any other one metal.

The older, or transition layer, theory of adsorption can account very well for the photo-electric phenomena, if it is taken in connection with the notion of solution of a gas in a solid and with some recent observations of Cardani.[1] We must look upon the layer as merely hindering the escape of electrons released from the metals. The gradual reduction in thickness or density of the layer will permit more and more of them to escape. To account for a depression in the curve, after the original layer has been broken up, a new layer must be formed. The gas for this must come from within the metal and, according to Cardani's results with the aluminum electrodes in X-ray tubes, this is quite possible. "The occluded gas" he found, quoting the abstract, "experiences very great difficulty in reaching the surface of the electrodes, even under the influence of high temperature and rarefaction, and the electrodes may

[1] Accad. Lincei, Atti, 24, 105, 1915.

consequently undergo superficial exhaustion and the pressure remain constant during the passage of the discharge for some days, so long indeed as the occluded gas in the deeper layers fails to compensate the exhaustion when it reaches the surface; when, however, such compensation does occur emission of gas recommences on the discharge being passed." In the experiments with which we are here concerned, the compensation is initiated by the heating at higher temperatures and there may be a great deal more than mere compensation. In fact, enough gas yielded by the metal to build up a new layer capable of remaining for several heatings. This way of looking at the phenomena is quite consistent with the observed fact that the readily diffused hydrogen appears in all but very narrow intervals of the curves. It is a matter of indifference on this view whether the gas on the surface originally and that which finally diffuses out is the same or different in kind.

In the above it has been assumed that the photo-sensitiveness is a property of the metal itself and that the gases only modify the conditions of escape of the electrons. But the changes in photo-sensitiveness can also be accounted for on the basis of the changes of the properties of the metals themselves, either by solution in it of gas or by the formation of chemical compounds. These changes need take place only at the surface but may extend throughout the metal. Heating merely changes the concentration of gas or dissociates or builds up different compounds. The last seems more probable for the changes would be expected to take place at certain temperatures, giving rise to definitely placed elevations and depressions in the curves. The first is not entirely excluded, as the function relating photo-sensitiveness to concentration of gas is not necessarily a continuously increasing or decreasing one.

No evidence is at hand bearing on the question of concentration of gas but good ground exists for believing that chemical changes play an important part. Millikan and Souder[1] working with sodium and Wertheimer[2] with cadmium have found differently shaped fatigue curves according to the wave-lengths in use. The only explanation seems to be that active gases, even undetected traces, form chemical compounds which respond to different spectral regions than the metals themselves. Of course in the original curves these active gases are of no consequence. Once the metal has been cleaned the gases can, however, assert themselves.

The two above mentioned papers have suggested a test that it is hoped to carry out soon. If, instead of the total radiation, two extreme

[1] Proc. Nat. Acad. Sci., 2, 19, 1916.

[2] Deutsch, Phys. Gesell. Ber. 17, 289, 1915.

ends of the spectral region for which the metal is sensitive, are used and differently shaped heating current-photo current curves result, it is proof that chemical changes take place, or a change of concentration, which alters the long wave limit of sensitiveness or the activity for a given wave-length. If the curves for the two monochromatic radiations are similar we should have to reject the idea of change of concentration of gas or of chemical change and attribute the variations of photo-sensitiveness to the opening up of gaps through the one atom layer or a reduction in its thickness or density. Of course no decision can be reached, by this means, between the two theories of adsorption.

The comparison of curves for different wave-lengths should reveal the presence of metallic impurities on the surfaces of the metals being investigated. If, as has been suggested, sodium and potassium are driven from the body of, say, platinum to its surface, it might, at certain temperatures, show the photo-electric effect well into the visible region of the spectrum.

A test of the two adsorption theories would be afforded by working in vacua of a far higher order than have been available hitherto. An extreme vacuum would prevent the formation of the second or succeeding layers of atoms of gas and the photo-sensitiveness remain constant once the clean patches of metal have grown to cover the entire surface. Heating current-photo current curves should have the appearance of the saturation curves for currents in ionized gases. In the transition layer theory, on the other hand, where the gases all come from the metal; the state of the vacuum is relatively unimportant, if it only is high enough to prevent ionization currents.

Still another mechanism, not to be lightly thrown aside is suggested by an examination of the curves of Robinson[1] and Stuhlmann and Compton[2] relating the photo-electric current to the thickness of sputtered platinum films. Robinson's curves are particularly similar to our original curves for nickel and two of the curves shown by the latter authors are exactly like the present curve for platinum charged electrolytically with oxygen and for platinum cleaned in flame and acid, as far as they go. In general, such exact similarity is not to be expected because of the complication of many gases and the presence of metallic impurities. With platinum charged with oxygen, the other gases are well subdued and heating the metal in flame and acid is an effective means of getting rid of salts and metallic impurities. It may be imagined that the cleaning by heating is a sort of an ingrowing surface phenomenon. Each heating

[1] Phil. Mag., 32, 421, 1916.
[2] PHYS. REV., 2, 199, 1913.

removes completely a certain thickness of gas, leaving a thin sheet of pure metal. On increased heating the sheet gets thicker, passing that of maximum photo-sensitiveness. At this time the gas in the body of the metal may diffuse all at once to the surface, as in Cardani's[1] experiments, and contaminate the cleaned layer. The process of cleaning is then repeated at higher temperatures and a second maximum of the heating current-photo current curve gone through. It might also be assumed that the photo-electric activity has its seat in some active layer other than the metal and that it is either built up or broken down by the heating. If it were a case of gradual removal the curves of Robinson would be followed in the inverse order. The lack of symmetry of the elevations of the curves about their maximum ordinates might make possible a decision as to which of the last two assumptions is the tenable one. It may be more than a coincidence that the accepted value, on the theory of the transition layer, of the thickness of adsorbed gas films is of the same order of magnitude as the thickness of platinum film for maximum photo-electric current: namely, 10^{-7} cm.

Summary.

A spectroscopic study has been made of the gases emitted by silver, gold, nickel, palladium and platinum at various temperatures between that of the room and fusion. Simultaneous measurements were made (after cooling of the metal) of the photoelectric emission. They are plotted against heating currents instead of temperatures. Nickel, palladium and platinum were found to emit carbon gases or oxygen, only, in the intervals of high photo-sensitiveness. Hydrogen is emitted elsewhere. Silver and gold give off hydrogen at all heating currents, but in intervals of high photo-sensitiveness the predominatimg part of the mixture of gases is one giving the carbon spectrum.

The effects of pure gases on the cleaned metals were looked into for two reasons. The matter is of interest in itself and it was hoped to imitate the curves obtained during the original cleaning. A mixture of hydrogen and oxygen gives fair imitation for the three metals on which it was tried; silver, palladium and platinum. Oxygen alone gives a good imitation of nickel. Carbon dioxide is of no influence on the metals unless it is alone. This gas, and also nitrogen and possibly hydrogen, is incapable of protecting the metals from the action of some residual gas or vapor in the cell. By a comparison of curves taken immediately on cleaning, without gas treatment, or after the metals remained in vacua for several hours; the active residual gas was shown to be either carbon

[1] Loc. cit.

monoxide or methane. It is only in gold that constancy of photo-sensitiveness is approached in the "immediate" curves. With platinum the variations are enormous. Cyanogen and illuminating gas introduced novel features into the curves.

Charging electrolytically, or glowing, gave the same types of curves, generally, as mere contact with gas. Metals heated in a gas are usually photo-electrically stable with regard to further heating. Heating in flames, plain or colored, gives the hydrogen-oxygen type of curve. Colored flames leave an easily removable activity. The presence of lime or a salt of calcium gives characteristic heating current-photo current curves.

No definite theory is proposed, but the possibilities are considered on the bases of:

1. The primary valence theory of adsorption,
2. The transition layer theory of adsorption,
3. Solution of gas in metal.
4. Chemical combination of gas and metal,
5. Photo-electrically active layer being built up or destroyed by the heating.

The experimental means of deciding among some of these are outlined.

This work was suggested and its progress directed by Professor E. P. Lewis. It gives me pleasure to acknowledge his aid and constant encouragement.

UNIVERSITY OF CALIFORNIA,
March, 1918.

ELECTRIC FORCE IN THE MERCURY ARC.

BY C. D. CHILD.

THE following is a description of measurements of the electric force in the mercury arc with different temperatures, pressures of the vapor, and currents.

Similar experiments have been made by other experimenters, but in no case are all the data given that are desired. Knipp[1] measured the electric force and the pressure of the gas in the apparatus to which the tube containing the arc was connected, but it is desirable to know the pressure in the arc itself and this is much greater than that which was measured, since the mercury vapor of the arc condenses before reaching the other parts of the apparatus.

Measurements of the electric force and of the temperature were made by Wills[2] and pressures of the gas were computed from the observed temperatures by assuming that the pressure in the arc is the same as that given in tables for the pressure of mercury vapor at different temperatures. Since the vapor in the arc is at a very much higher temperature than that of the liquid mercury in contact with it, this assumption cannot be accepted as correct.

Moreover when testing any theory of the arc one desires to know the density of the vapor rather than the pressure. Since the temperature varies greatly, the density is not proportional to the pressure. There appears to be no way of measuring the density directly, but since the vapor in the arc is far from the point of condensation, it is probable that the density varies inversely as the absolute temperature. As a result approximate values proportional to the density can be obtained by finding the pressures and the temperatures of the mercury vapor.

It is, however, difficult to find either of these quantities accurately when the pressure is low. The temperature can best be measured with a thermojunction, but even this gives readings which are somewhat too low. Some of the heat will be conducted away by the wires and some will be radiated from them, and no heat will be given up to them except when they are at a lower temperature than the surrounding gas. When the pressure of the gas is high, the error thus introduced is, no doubt,

[1] PHYS. REV., 31, 106, 1910.
[2] PHYS. REV., 19, 65, 1904.

small, but with pressures in the neighborhood of 1 mm. it is probably quite appreciable.

It is also difficult to measure accurately the pressure of the gas. No method similar to that of the McLeod gauge can be used, since the vapor condenses when taken from the arc. Some form of manometer must be used where a surface of mercury is exposed as directly as possible to the vapor of the arc. Even when this is done, there is condensation at this surface and loss of pressure. When one is finding the density the errors in the measurement of the temperatures counterbalance somewhat those made in the measurement of the pressure, for the measurements of both of these quantities will be too small and the density is directly proportional to one and inversely proportional to the other.

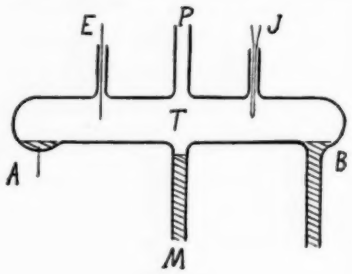

Fig. 1.

Description of Apparatus.—In spite of these difficulties it seemed desirable to make a further study of the mercury arc by taking simultaneous readings of the electric force, the temperature, and the pressure. The tube used for this purpose is shown in Fig. 1. T is a tube having mercury terminals at A and B, a connection to the pump and drying tube at P, a manometer at M, a thermojunction at J, and an exploring wire at E. J was used both as a thermojunction and as a second exploring wire. B and M extend downwards to beakers containing mercury which is under atmospheric pressure. The mercury in these can be raised and lowered by changing the height of the beakers.

The arc was started by raising the mercury in both B and M, until there was a connection between A and B. B was then lowered, until the arc extended the whole length of the tube. The mercury in M was then lowered, until the top of the mercury was below the curvature where M joins T. It was necessary to lower the mercury to this extent, in order to see clearly the top of the mercury.

The height of the mercury in M was determined by a cathetometer, first with the tube exhausted but with no arc, and secondly while the arc was maintained. The difference between the readings was taken as the pressure of the vapor in the arc. Consecutive settings of the cathetometer on the surface of the mercury were apt to vary by 0.1 mm.

The electrometer was calibrated by comparing it with the Weston voltmeter. The thermojunction was formed by welding a platinum wire 0.5 mm. in diameter with a platinum-iridium wire 0.3 mm. in diameter, the latter containing 10 per cent. of iridium. This was con-

nected to a high resistance D'Arsonval galvanometer. It was calibrated by observing the deflections produced by boiling sulphur, melting antimony, and melting sodium chloride, one junction being placed in one of the above substances and the other kept at 22° C., which was approximately the room temperature.

The length of the tube was 39 cm. and its diameter was 2.6 cm. The distance between E and J was 21 cm. The inner diameter of the tube M was 6.5 mm. The distance from B to J was 4 cm. B was positive throughout the experiment.

When the current was started the potential difference between E and J was comparatively large, rapidly decreasing to a minimum, and then gradually increasing. The first large value of the potential difference was more noticeable when the arc was started after having been extinguished for several hours, than it was when the arc had been extinguished for but a short time and the tube was still hot. The initial large value of the electric force was probably due to the presence in the tube of other gases than mercury vapor. After the arc had been maintained for a short time the mercury vapor distilled over into the other parts of the apparatus and any foreign gases were swept out with this.

This view is borne out by the fact that the potential difference increases very greatly when enough gas is allowed to enter from P to push back the gases into T. By taking care to allow but a small amount of air to enter, this can be done without extinguishing the arc. The moment when such gas is pushed into tube T can be determined by the appearance of the vapor in P. The vapor coming from the arc is luminous and when there is little air in P, the boundary between the air and the vapor coming from the arc is clearly marked. When a slight amount of air is thus allowed to enter T, the voltage rises very much, decreasing again as soon as the air is again swept back from the arc.

The initial high potential difference was not due to the presence of cold mercury vapor, for the effect was very much less noticeable if the arc was started before the tube was cooled sufficiently to condense all of the vapor and allow other gases than mercury to enter the tube. Neither was the initial high voltage due to the fact that the tube was cold, for in general the hotter the tube the higher the voltage, as will be seen from the following data.

The lowest value of the electric force was approximately 0.4 volt per cm. with each of the currents tried, but with this voltage the pressure of the vapor was too small to be detected with the manometer used. As the tube became warmer the vapor pressure, the temperature, and the

electric force increased. The values observed are given in the following tables. The first column gives the pressure of the vapor in millimeters of mercury, the second gives the absolute temperature, the third gives the relative density as computed from the formula $d = p(T_0/T)$, where p is the pressure, T_0 is 273, and T is the temperature given in the second column. The electric force is given in the fourth column.

TABLE I.

Three Amperes.

Pressure in Mm.	Absolute Temperature.	Density $=p(T_0/T)$.	Electric Force.
.42	755	.152	.495
.78	815	.264	.54
1.15	855	.367	.59
1.41	882	.437	.64
1.72	915	.514	.685

TABLE II.

Five Amperes.

Pressure in Mm.	Absolute Temperature.	Density $=pT_0/T$.	Electric Force.
.47	925	.138	.495
.83	940	.242	.54
1.25	955	.356	.59
1.51	975	.423	.64
2.03	1000	.556	.685
2.40	1015	.646	.73
2.74	1035	.750	.78
3.25	1050	.847	.83
3.72	1065	.955	.875
4.12	1080	1.04	.925

TABLE III.

Seven Amperes.

Pressure in Mm.	Absolute Temperature.	Density $=pT_0/T$.	Electric Force.
.57	965	.163	.495
.96	990	.265	.54
1.43	1020	.384	.92
1.92	1040	.506	.64
2.37	1070	.606	.685
2.85	1085	.707	.73

Observations with pressures higher than those given could not be made with a current of three amperes. The tube did not become hot enough to form much vapor and when more than a small amount of air

was allowed to enter the apparatus it forced its way into tube T and extinguished the arc. With the other currents and the highest pressures given in the tables the tube became as hot as it was safe to run it.

The temperatures here recorded are higher than one would expect from the work of others. It is not possible to make direct comparisons with the data of other experimenters, since the pressure in the arc was not measured by them. Moreover the size of the tube, amount of current, and position of the thermojunction do not exactly correspond to those given by others, but some idea of the conditions can be gained by considering the values of the electric force which are given. As far as this enables one to compare the observations, the temperatures here recorded are much higher than those given by Wills or Knipp. With a tube 3.8 cm. in diameter and a current of 3 amperes Wills gives the temperature as 145° C., when the electric force is 0.676 volts per cm. With the tube somewhat smaller and the same current and the same electric force the temperature here given is 640° C. Judging from the data given by Wills on the temperatures in different sizes of tubes the difference between the two tubes compared would account for but a few degrees. The temperatures given by Knipp are somewhat higher than those of Wills, but not nearly as high as those given in the preceding tables.

On the other hand these values are approximately the same as those given by Küch and Retschinsky[1] in an article on the mercury arc in a quartz tube. The electric force is not given by them, but approximate values can be computed from the potential differences between the ends of the tube, which are given. As far as could thus be determined the values of the temperature given in this article are much the same as theirs for the same pressures. Küch and Retschinsky used wires which were only 0.05 mm. in diameter for their thermojunction. A thermojunction of wires so small as this would undoubtedly give higher and more correct values of the temperature than one of larger wires. This might explain the fact that their values of the temperature are higher than those of Wills or Knipp, but the wires used in this investigation were not excessively small and yet the values of the temperature found are equally high.

There are plotted in Fig. 2 the values of the density and the electric force which are given in the preceding tables. The dots indicate the values obtained with a current of five amperes and the crosses those obtained with seven amperes. The values for three amperes so nearly coincide with some of those for five and seven amperes, that they cannot

[1] Ann. d. Phys., 22, 595, 1907.

be inserted without confusing the drawing. The fact that they so nearly coincide is due to errors of observation. That this statement is correct was shown by making sudden changes in the current and observing the potential difference immediately after the change was made. An approximate value of the new potential difference could be obtained before any change in the pressure or in the temperature could be detected. It was thus found that there is a slight increase in the potential difference when the current is lowered and a decrease when it is raised. As nearly

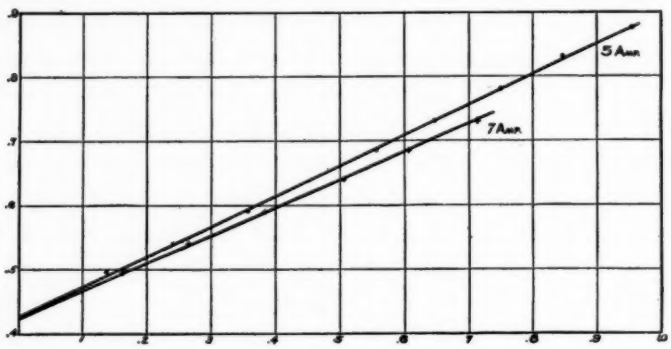

Fig. 2.

as could be determined the decrease is about 8 per cent. of the initial value when the current is increased from three to seven amperes. This corresponds somewhat to the values given in the preceding tables.

The points plotted for each current are not far from a straight line which passes above the origin. In this respect the electric force in the mercury arc behaves in a manner similar to that in the unstriated discharge through such gases as hydrogen and nitrogen. However, the discharge through mercury vapor must in some respects be different from that given for discharge through hydrogen, since the impact between electrons and molecules of mercury appears to be elastic while that between electrons and hydrogen molecules is inelastic. Moreover, it has been suggested by Millikan[1] that mercury molecules may be ionized by radiation which is produced by the impact between electrons and molecules, even when such impacts are not sufficiently violent to ionize directly. As a result it is impossible at the present time to present a satisfactory explanation of the facts that have been given in the preceding account.

Summary.—The electric force in the mercury arc increases as the density of the vapor increases. It is approximately a linear function of

[1] PHYS. REV., 9, 378, 1917.

the density of the vapor but does not become zero when the density is zero.

The electric force decreases about 8 per cent. when the current increases from three to seven amperes.

The temperatures of the mercury arc were found to be higher than those usually ascribed to it.

COLGATE UNIVERSITY,
March, 1918.

EFFECTS OF DIELECTRICS ON THE SPARKING VOLTAGE.

BY E. R. WOLCOTT.

THE voltage required to produce sparking between two electrodes is materially reduced by the presence of a dielectric near one of the electrodes, under certain conditions, which are outlined in the following pages.

The phenomenon is of considerable importance in the electrical precipitation of dust and fumes from gases, because the potential difference that can be maintained between the electrodes is thereby reduced, which, in turn, decreases the efficiency of operation.

As is well known, the electrical precipitation of dust and fumes from gases is accomplished by passing such gases through an electrical field formed between two electrodes, one being of small area, such as a wire, which is called the discharge electrode, the other being of relatively large area, such as a pipe concentric with the wire, or a plate parallel to the wire, which is called the collecting electrode.

The discharge electrode is maintained at a high potential and the collecting electrode is grounded, the field between the two being unidirectional.

The dust or fumes are repelled by the discharge electrode and precipitated upon the collecting electrode.

That these deposits lower the efficiency of operation was not recognized in the early stages of electrical precipitation and consequently some of the results then obtained seemed quite anomalous. For instance, a small plant was installed to precipitate a non-conducting fume. It operated with complete success for a few hours, that is, until the collecting electrodes became covered with the deposited fume and then the efficiency of precipitation fell off rapidly. It was also noticed that, in certain cases, particles of fume appeared to be repelled by the discharge electrode towards the collecting electrode, but were not actually deposited thereon. Instead, they moved out with the gases parallel to, and but at a short distance from, the collecting electrode. Under such conditions, a faint glow was sometimes visible at night upon the collecting electrode. Many instances in actual practice have shown the advantages of the use of moisture, and it became highly desirable to determine the reason therefor.

These observations led to an investigation of the effects of various substances upon the voltage that could be maintained between the discharge electrode and the grounded collecting electrode. The effects of these deposits upon the collecting electrode, with a wire as the discharge

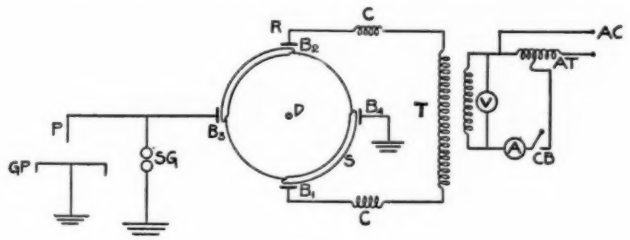

Fig. 1.

electrode, were found to be analogous to those between a point and a grounded plate, and so only results with a point and plate are included in the following tables.

The arrangement of apparatus for testing these effects is illustrated in Fig. 1.

GP is a grounded plate.

P is a metallic point connected as shown.

SG is a sphere-gap meter for measuring the peak voltage.

R is a rectifier which consists of an insulating disc *D*, 76 cm. in diameter, rotating synchronously with the alternating current.

SS are metal segments fastened on the periphery of the disc as shown.

B_1, B_2, B_3, B_4 are stationary metallic shoes, 15 cm. long.

B_1 and B_2 are connected through choke coils *CC* to the high tension terminal of the transformer *T*.

B_3 is connected to the point *P*.

B_4 is connected to the ground.

T is a 5 K. W., 110- to 100,000-volt transformer, the primary voltage of which is controlled by the auto-transformer *AT*, which is connected to the source of operating current *AC*. The primary instruments are an ammeter *A* and a voltmeter *V*. *CB* is the circuit-breaker.

The method of operation was to raise the voltage gradually by adjustment of the controlling switch of the auto-transformer until a disruptive discharge occurred between the point and the plate. The peak voltage at which this discharge took place was measured by the sphere-gap meter. The spheres were 12.5 centimeters in diameter.

The plate was large enough to prevent arcing to its edge. The distance

between the point and plate was adapted to the prevailing conditions, being six centimeters in most cases.

A comparison of the peak voltages that produced disruptive discharges between a high tension point and a grounded plate, six centimeters apart, is given in the following table:

TABLE I.

Arcing Voltage between a Point and Plate.

Polarity of Point.	Kilo Volts Peak.	Kind of Discharge.	Remarks.
Negative.....	136	Arc	First discharge
"	120	"	Minimum value
Positive.....	45	"	" "
"	42	Spark	" "

As first noticed by Faraday[1] the voltage required to start a spark is greater than that which it is later necessary to apply. In the present instance, this difference is shown in the first two readings of the above table.

The difference between the arcing voltage of the negative and positive points is shown in readings two and three.[2]

The difference in voltage required to produce arcing and sparking is indicated in the last two readings. Sparking was not as noticeable with the point negative as with the point positive. These sparks were white and snappy as distinguished from the yellow, heavy arcs. The latter opened the circuit-breaker in the primary circuit of the transformer

[1] Faraday, Exp. Res., Par. 1417.

[2] It has long been recognized that the minimum potential necessary to produce a spark between a point and a plate depends upon the polarity of the point. (J. J. Thomson, Conduction of Electricity Through Gases, 2nd edition, p. 498.) In all the instances cited in the above reference this minimum potential was found to be greater for the point positive than for the point negative, but the distance between the point and plate in these experiments did not exceed a few millimeters. To compare the sparking voltage at short distances with that of several centimeters between the point and plate, the Girvin generator was so adjusted that short sparks as well as long sparks could be obtained. It was then found (since the above paper was prepared) that at sparking distances less than about 2.3 millimeters, the sparking voltage was less for the point negative than for the point positive, but that for distances greater than 2.3 millimeters, the sparking voltage was greater for the point negative than for the point positive. In other words, a curve showing the relation between sparking voltage and distance between the point and plate when the point is positive crosses a similar curve for the point negative at a position indicating about 2.3 millimeters distance between the point and plate. These curves have not been as yet accurately determined. When this is done, it is planned to publish the data thereon in a future paper.

F. G. Cottrell (U. S. Patent 1067974, July 22, 1913) recognized that higher voltage could be maintained with a negtaive discharge electrode than with a positive discharge electrode.

when set at full load current; the former scarcely affected the reading of the ammeter.

The considerable difference in arcing voltage of a discharge between a point and plate, when the point is negative and when it is positive, was utilized in the production of a high tension alternating current rectifier.[1]

With the point negative, various substances were placed upon the grounded plate, and the arcing voltage observed. A few of such substances are listed in the following table, the high tension point being 6 cm. from the grounded plate:

TABLE II.

Effects of Dielectrics on the Arcing Voltage between a Negative Point and a Grounded Plate.

None	120
Mica	50
Sulphur	50
Glass wool	50
Varnished cambric	70
Filter paper	90
Asbestos	100
Edge of glass plate	65
Writing paper	118
Writing paper crumpled	90

These values are merely indicative, as it will be noticed that the value of the arcing voltage depends not only upon the kind of substance, but also upon its condition. Thus, a sheet of glass resting upon, and completely covering, the plate, of course, raises the voltage necessary to produce an arc. However, as the glass is drawn across the plate so that its edge comes underneath the point, arcing occurs at a much lower voltage than when no glass is present. Likewise, when a sheet of smooth paper is laid over the plate, the arcing voltage is not altered much; but when the paper is crumpled, or there is a hole in it, the arcing voltage is materially reduced.[2]

By very careful adjustment, it is possible to maintain a voltage that will not produce a disruptive discharge, but only a silent glow. With a piece of fibrous paper having a hole about one centimeter in diameter, which, however, was not directly underneath the point, the photograph reproduced in Fig. 2 was taken. In this case the point was five inches (12.7 cm.) from the grounded plate, 60 K. V. were applied and arcing

[1] E. R. Wolcott and C. J. Erickson, PHYS. REV., N. S., Vol. IX., p. 480, June, 1917.

[2] W. J. Humphreys (PHYS. REV., Vol. 11, p. 79, 1900) noticed that certain dielectrics produced a spark between the terminals of an electrostatic machine when brought near the positive terminal, but not when brought near the negative terminal.

resulted at 71 K. V. It will be noticed that the glow is cylindrical and proceeds from the edge of the hole in the paper. If the paper is moist, or if a grounded metallic screen is laid over it, no such glow appears, and the arcing voltage is not lowered.

TABLE III.

Results when Dielectric is Discharged.

Substance.	Peak K. V.	Remarks.
100 mesh screen	116	Laid directly on plate
Mica (dry)	50	" " " "
Grounded screen over mica	116	" " " "
Sulphur (flowers)	50	Dry.
" "	112	In moist atmosphere.
Mica	112	" " "

It thus appears that the substance must be able to accumulate a charge in order to show the effect.

That a considerable charge was accumulated was evident from the spark that could be obtained from the mica after removing it from the plate, and also from the appearance of sparks across the mica sheet while on the plate. These were often 2 cm. long, indicating the great potential differences acquired by different portions of the sheet.

For comparative purposes, the arcing voltages between points and the effects of a dielectric, such as mica, thereon are given in the following table:

TABLE IV.

Effects of Mica on the Arcing Voltage between a High Tension Point and a Grounded Point.

Polarity.	K. V. Peak.	Discharge.	Remarks.
Alternating current	58	Arc	No mica; value at start.
" "	53	"	No mica; minimum value.
" "	46	"	Mica near high tension point.
" "	46	"	Mica near grounded point.
" "	43	Spark	Mica near grounded point.
" "	43	"	Mica near high tension point.
High tension point negative.	43	Arc	The only effect of mica was to increase the sparking. No lowering of the arcing voltage was observed.
" " " "	40	Spark	
" " " "	40	Arc	
" " " "	36	Spark	

The difference between the voltage at first and the minimum voltage is again noticeable in the first two readings. The mica lowers the arcing voltage somewhat when placed anywhere in the alternating field, but the only effect was increased sparking in a unidirectional field.

Fig. 2.

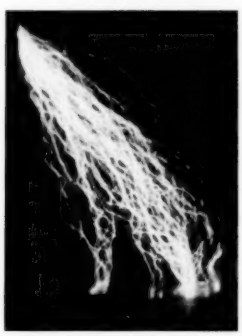

Fig. 3.

E. R. WOLCOTT.

The effect of mica at various positions in the field between a negative point and a grounded plate is given in the following table:

TABLE V.

Effects of Mica at Various Positions in the Field between a Negative Point and a Grounded Plate.

K. V. Peak.	Discharge.	Remarks.
120	Arc	No mica.
122	"	Mica at point.
122	"	Mica midway between point and plate
65	"	Mica near plate.
50	Spark	Mica near plate.

In the point-to-plate discharge with the point negative, the mica has little effect, except near the plate. There seems to be a certain position near the plate which gives the greatest lowering of the arcing voltage. This is not when the mica is close against the plate, but when it is about one millimeter above the latter.

The method used for examining this effect was to adjust the voltage to about that which would produce arcing when the mica was in position, and insert the mica afterwards by means of a paraffined wooden stick slotted at one end to hold the mica. As the sheet of mica was slid on to the plate sparks would jump to it as shown in Fig. 3. By pressing the mica against the plate, and then lifting it, the position for maximum lowering of the arcing vo tage could be determined.

As a basis for comparison of the actions of dielectrics and metallic points and edges, the following table is included:

TABLE VI.

Effects of Metallic Points Projecting up from Grounded Plate Point Negative and 6 Cms. from Plate.

Arrangement.	Kilo-Volts (Peak).
Plate only	120
Screen on plate	116
Point projecting 2 mm. from plate	78
Point projecting 3 mm. from plate	78
Point projecting 10 mm. from plate	48

The dielectrics placed on the grounded plate were not thick, being usually less than 0.1 mm. The effect is thus of a different order of magnitude than with metallic points projecting a greater distance from the plate.

The amount of dielectric necessary to produce this effect was very small, in the case of dust from a sintering machine containing 20 per

cent. elemental sulphur, which was sprinkled through a 100-mesh screen upon the grounded plate, the following results were obtained:

TABLE VII.

Surface Density of Dielectric and Arcing Voltage.

Gm./Sq. Ft.	Mgr./Sq. Cm.	K. V. (Peak).
0	0	130
0.85	0.91	120
5.45	5.74	74
8.15	8.78	60
17.75	19.14	50

Plotting these results gives the curve shown in Fig. 4. A moisture content of 2.25 per cent. in the above dust was not sufficient to overcome

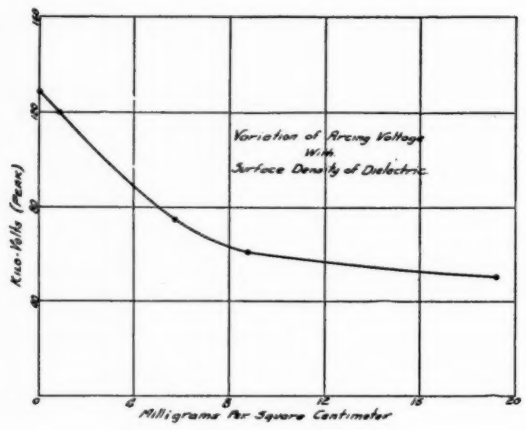

Fig. 4.

the effect, but a moisture content of 2.91 per cent. raised the arcing voltage to normal value; that is, to the value with no dust on the plate. This effect of moisture was noticed in many instances. In the case of zinc oxide, as the dielectric, 1 per cent. moisture was sufficient to eliminate the lowering of the arcing voltage.

Whenever a lowering of the arcing voltage was obtained a portion of the grounded plate was covered by a non-conducting substance. When this substance was made conducting, as by wetting it, no such lowering of the arcing voltage resulted.

As mica does not wet easily, some difficulty was experienced in completely discharging it and, unless it was completely grounded, a lowering of the arcing voltage resulted.

Likewise, when the dielectric accumulating the charge was removed, as when the sulphur was burned out of the above dust, no lowering of the arcing voltage resulted.

Similar results were obtained with a 50,000 volt, direct current, 5 K.W. Girvin generator, as shown in the following table. The point was 3.17 cm. from the grounded plate:

TABLE.

Arcing Voltage with 50 K. V. Direct Current Generator.

Condition.	K.V. r.m.s.[1]
Positive point	25.7
Negative point	55.6
Sheet of mica over plate, point negative	27.6
Varnished cambric, point negative	47.5
Felt paper, point negative	40

The machine was protected by means of a relay, operating on the high tension current, which automatically inserted resistance in the exciting circuit of the generator when full load current was exceeded.

With this direct current generator, no sparking between the point and plate was noticeable; the discharge was always a heavy arc.

From these data it appears that a dielectric placed upon the grounded plate of a point-to-plate unidirectional discharge, the point being negative, accumulates a charge, the potential of which may be sufficient to ionize the surrounding gas, producing a glow typical of the positive discharge. This glow, being a much better conductor of electricity than other portions of the gas, decreases the total resistance between the two electrodes, and lowers the voltage necessary to produce a disruptive discharge.

However, to produce this effect, the condition of the substance is just as important as its composition. It must not only be a substance capable of retaining a charge, but it is essential that it have a certain degree of discontinuity of surface, such as a roughened or porous surface, an edge or a hole.

The roughness of surface applies only to thin sheets, such as paper, which can be punctured by the discharge. A thick sheet of roughened glass covering the entire plate does not lower the arcing voltage (in fact, raises it) since to arc requires a complete ground connection.

The effect of moist atmosphere is also very marked. During damp weather, most of the above substances showed no lowering of the arcing voltage.

[1] An Electrostatic Voltmeter, E. R. Wolcott, Electrical World, May 13, 1916.

Some experiments were also tried using other gases than air, but these have not as yet been completed

In the following summary, it is to be understood that the conclusions apply only to the distances between the point and plate which are comparatively large; that is, over 3 centimeters. The conclusions as to the sparking voltage are equally applicable to the arcing voltage, as herein defined, except that the high voltage direct-current generator showed no sparking preliminary to the arc discharge.

SUMMARY.

1. The sparking voltage (peak) between a point and plate when the point is positive, is about half of that when the point is negative.

2. A dielectric of discontinuous surface placed over the plate (point-to-plate unidirectional discharge) lowers the sparking voltage, when the point is negative, to a value comparable to that when the point is positive.

3. The discontinuity of surface may be an edge or hole, or the body may be fibrous or porous.

4. No lowering of the sparking voltage results when means are provided for conducting away the charge, as when the deposit is sufficiently moist or is in a humid atmosphere.

5. No lowering of the sparking voltage results when means are provided for preventing the accumulation of a heavy charge as by covering the dielectric with a grounded screen.

6. An intense brush glow appears upon the dielectric when just under sparking voltage. The decrease in resistance of the gaseous medium between the electrodes thus produced is probably the cause of the lowering of the sparking voltage.

LABORATORIES, WESTERN PRECIPITATION COMPANY,
LOS ANGELES.

ON THE EFFECT OF A TRANSVERSE MAGNETIC FIELD ON THE DISCHARGE THROUGH A GEISSLER TUBE.

BY JAMES E. IVES.

1. INTRODUCTION.

DURING the course of some recent investigations[1] on the so-called magnetic rays of Righi, discharges through a peculiar form of Geissler tube, it became necessary to determine the effect of a transverse magnetic field on the discharge. It was found that the current through the tube was increased, and the potential difference across the tube decreased, by the field. When the strength of the field was further increased, the discharge became periodic for a certain value of the field, and finally ceased altogether when the field, being still further increased, reached a certain value.

Not only does the magnetic field affect the current and potential of the tube, but it also changes very greatly the appearance of the positive column. As the strength of the field increases, the striæ increase in number and move down the tube towards the negative glow; at the same time the positive column becomes narrow and is pressed over to one side of the tube. When the discharge becomes periodic, the striæ coalesce and the positive column presents a continuous (unstriated) appearance to the eye. The tube then emits a high note.

Certain questions, of great interest, are raised by these phenomena. (1) Why does a certain strength of field cause the discharge to become periodic? (2) Why does a still greater strength of field cause the discharge to cease altogether? (3) What would be the effect of the field applied to the cathode alone? (4) Applied to the anode alone?

If the Geissler tube is cylindrical in form, the magnetic field may be applied to it in two principal directions, transverse or parallel, to its length. In this investigation the field was transverse to the length of the tube.

2. PREVIOUS INVESTIGATIONS.

Thomson in his treatise "Conduction of Electricity through Gases,"[2] has given a general summary of the results of investigations on the action of a magnetic field on a discharge tube.

[1] PHYS. REV., 9, 353–356, 1917.

[2] Second edition, 1906, pp. 572–579.

The effect of a *transverse* field has been investigated by a number of observers. Paalzow and Neesen,[1] with a tube 11 cm. long and 1.3 cm. in diameter, having the electrodes 1.5 cm. apart, observed the effect upon the current through it. They found that a transverse field, whether applied to the whole tube, at the anode, or the cathode, always decreased the current. They give no numerical values for current or strength of field.

Melani[2] used tubes, containing air, in which the electrodes were 2, 4, 8 and 12 cm. apart. The field, current, and potential difference were measured in C.G.S. units, milliamperes and volts respectively. The transverse field was applied to the whole tube. He found that the potential across the tube, for constant field, first decreased and then increased, as the pressure increased; and, for constant pressure, increased as the field increased.

Wiedemann and Schmidt[3] placed different portions of the positive column of a tube, 12 cm. long and 2.5 cm. in diameter, between the poles of a magnet and found that a transverse field produced an increase in the electric field. The field was made just as strong as it could be without making the discharge disruptive. Sounders, of platinum wire, were sealed into the tube about 2.5 cm. apart. The current was .63 milliampere and the pressure .5 mm.

Almy[4] found that the transverse field, whether applied at the center of a tube, 20 cm. long and 3.5 cm. in diameter, at the anode, or at the cathode, produced a diminution of the potential difference between the electrodes. The diminution increased very rapidly with the pressure.

Willows[5] investigated the variation of the effect of a transverse field with pressure, and found that when the field is applied at the *cathode*, there is a pressure below which the current is increased, and above it, decreased, by its application. This "critical pressure" was found to depend on the value of the field and also on the initial current through the tube. For the same initial current, an increase of the field increases the value of the critical pressure. For the same field, if the initial current through the tube is decreased, the critical pressure is rapidly lowered. For the values of the field and current that he used, the critical pressure was about .6 mm. When any other part of the tube but the cathode was placed in the field, there was always a decrease in current. He also determined how the potential gradient varied at every point of the tube, when the field was applied, for pressures of 2.11 and .43 mm. respectively.

[1] Ann. Phys., 63, 209–219, 1897.
[2] Nuovo Cimento (4), 5, 329–356, 1897.
[3] Ann. Phys., 66, 314–340, 1898.
[4] Proc. Camb. Phil. Soc., 11, 183–190, 1901.
[5] Phil. Mag., 1, 250–260, 1901.

Riecke[1] determined the volt-ampere characteristics for different pressures and field strengths. He used a tube of peculiar shape, a sphere of 5.9 cm. radius. The electrodes were 6.5 cm. apart, placed so that when one was subjected to a transverse, the other was, at the same time, subjected to a longitudinal field. The pressures varied from .027 mm. to 5.0 mm., and field strengths of 0, 47, 144, 335 and 473 C.G.S. units were used. A serious objection to his method is that in his results it is difficult to separate the actions of the field on the two electrodes. His results show that the effect of the magnetic field increases as the pressure becomes less; at the pressure of 14.6 mm. the effect was extremely small. The characteristic for a given field strength crosses that for zero field at a critical value of the current which decreases as the pressure increases, and increases as the field strength increases. For values of the current less than this critical value the potential difference is increased, and for values greater decreased by the action of the field. He concludes that the influence of the magnetic field is made up of two parts; its action upon the anode being to increase the potential difference, and upon the cathode to decrease it.

H. A. Wilson[2] investigated the Hall effect in the positive column under the action of a transverse field. He found a well-marked effect, showing that, in the positive column, the negative ions have a much greater velocity than the positive.

Stark[3] investigated the influence of a transverse field on the *cathode fall of potential*. He determined the volt-ampere characteristics for the cathode fall for constant pressures and field strengths. As is well known, the characteristics for the cathode fall are a family of parabolas, every pressure having its corresponding parabola. He found that the effect of a tranverse field was to decrease the cathode fall and to bring the curve nearer to the current axis. By plotting the cathode fall as a function of the magnetic field he obtained curves which are very similar to those obtained by myself for the case in which the field acts on the cathode region only (see Fig. 7). I have plotted the values obtained by Stark in Fig. 13. He used a wire cathode, and experimented with fields normal and parallel to the cathode. He states that the potential difference in the *positive column* is increased by the action of a transverse field because the field diminishes its cross-section. He ascribes the effect of the transverse field upon the cathode fall to (1) a decrease in the area of the glow on the surface of the cathode, and (2) to a concentration of the

[1] Ann. Phys., 4, 592–616, 1901.
[2] Proc. Camb. Phil. Soc., 11, 249–263, 391–397, 1902.
[3] Ann. Phys., 12, 31–51, 1903.

cathode rays in the neighborhood of the cathode, the electrons being constrained to move around the lines of magnetic force. He used pressures from .031 to .493 mm.; magnetic fields from zero to 340 gausses, and currents from 75 to 850 microamperes.

Interesting papers on the effect of a *longitudinal* field on current and potential difference have recently been published by Earhart[1] and Earhart and Jolliffe.[2]

The results obtained thus far on the action of a transverse field on a Geissler tube are somewhat contradictory and do not yield definite results. In some cases the field was not entirely transverse. Also no attention has been paid to the value of the *external resistance* in the circuit, which, as I have shown in my paper on the Righi Rays,[3] plays an important part in the behavior of a discharge tube.

The discharge through a Geissler tube is affected by: (1) Size and shape of the tube; (2) kind of gas used; (3) pressure of gas in tube; (4) external resistance of circuit; (5) electromotive force impressed upon circuit, and (6) external forces acting upon tube, *e. g.*, magnetic, electric or thermal. For a given tube, and a given pressure, the effect of a magnetic field may be investigated either by determining the volt-ampere characteristics of the tube for fields of different strengths, or by varying the strength of the field, keeping the external resistance and applied electromotive-force constant, and finding the variation of the current and potential of the tube with the variation of the field. In this paper, unless otherwise stated, the measurements were made at a pressure of .13 mm. of Hg. Since it was necessary to be frequently admitting air into the tube and pumping it out again, the air of the room was used, and no attempt was made to dry it. On account of leaks, and changes in the pressure of the gas due to the discharge through it, it was difficult to keep the pressure constant. This change in pressure produced a change in the zero readings for current and potential. The errors in the readings of current and potential due to this cause, were corrected by plotting a curve showing the variation of current and potential with time, everything else being kept constant. All readings of current and potential were then timed, and the proper corrections for them taken from the correction curve.

3. APPARATUS.

The form of tube finally adopted is shown diagrammatically in Fig. 1. The dimensions are given on the figure in centimeters. The anode and

[1] PHYS. REV., 3, 103–114, 1914.
[2] Astrophys Jour., 46, 76–82, 1917.
[3] Loc. cit.

cathode were alike and made of aluminum wire .328 cm. in diameter. This tube will be called Tube *C*. Two others were used exactly like Tube *C*, except that in one, which we will call Tube *A*, the electrodes were made of platinum wire .046 cm. in diameter, and in the other, Tube *B*, the anode was made of this platinum wire, and the cathode of the aluminum wire of the diameter given. The distance between the elec-

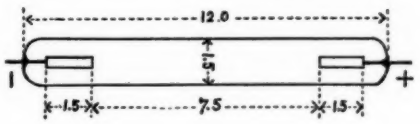

Fig. 1.

trodes in all three tubes was the same. The results obtained with Tubes *B* and *C* were of the same character. On account of the smallness of the surface of the cathode in Tube *A*, it was not found possible to get sufficiently large values of current. The high values of the potential obtained with this tube for small values of the current is shown in Fig. 11. These can be compared with those shown in Fig. 12 which were obtained with Tube *B*. The use of Tube *A* was therefore given up early in the experiments. Tube *C* was finally adopted so as to make the electrodes symmetrical and the area of the cathode fairly large. By making the electrodes symmetrical we can be sure that none of the results are due to their asymmetry.

The magnetic field was obtained by placing the tube between the poles of the electromagnet of an Einthoven galvanometer. The faces of the poles, 12.50 cm. long and 2.50 cm. wide, had a separation of 1.85 cm. The field between the poles could be varied from zero to 3,000 gausses. In actual practice, the field used was less than 400 gausses. The field, between the poles, was explored from top to bottom and from side to side and it was found that, in those parts of it occupied by the tube, it deviated from the mean value by less than 5 per cent.

The current through the tube was measured with a galvanometer or a milliammeter, and the potential difference across its electrodes with a quadrant electrometer.

The circuit of which the tube formed a part is shown in Fig. 2, where *T* is the tube; *B*, a battery of from 500 to 2,000 Planté cells; and *R*, a non-inductive resistance of graphite, water or a solution of cadmium iodide, which could be varied from a few thousand to 1,500,000 ohms. The pressure was measured with a MacLeod gauge.

4. PRELIMINARY THEORETICAL CONSIDERATIONS.

In previous work on discharge tubes, little or no attention has been paid to the effect on the discharge of the external resistance of the circuit, R. (See Fig. 2.) It is evident, however, that the value of this resistance will play an important part in the behavior of the discharge.

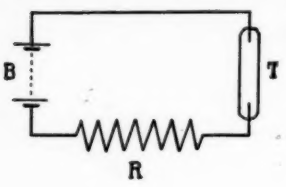

Fig. 2.

Kaufmann[1] has shown that the discharge through the tube will not be stable if

$$R < -\frac{\partial e}{\partial i},$$

where e is the potential across the tube; and i, the current through it; that is, if the discharge through the tube has a falling characteristic and its slope is greater than R.

Apart from this criterion of stability of discharge, however, the magnitude of the external resistance will affect the shape and slope of the curves showing the relation between current and strength of magnetic field, potential and field, and under certain conditions, current and potential.

In the circuit of Fig. 2, let E be the electromotive force of the battery B; then if e and V are the potentials across the tube, T, and the resistance, R, respectively, we have

$$V + e = E. \tag{1}$$

If E and R are kept constant and a small variation of e, Δe, is produced by varying the magnetic field applied to T, we shall have

$$\Delta V = -\Delta e. \tag{2}$$

But by Ohm's law

$$V = iR$$

and (2) becomes[2]

$$R\Delta i = -\Delta e$$

or

$$R = -\frac{\Delta e}{\Delta i}$$

or in the limit

$$R = -\frac{de}{di}. \tag{3}$$

Therefore, if, starting with a given current through the tube, i_0, and potential across it, e_0, we produce a variation of the current by applying some external force to the tube, keeping the applied electromotive force and external resistance of the circuit constant, we obtain a linear relation

[1] Ann. Phys., 2, 158–179, 1900.

[2] See also Stark, Elektrizität in Gasen, 1902, pp. 407–409.

between e and i which will be represented by a straight line, the *slope* of the line being numerically equal to the *external resistance* R.

Three of a family of such lines are shown in Fig. 4. These lines were obtained for Tube B, using different external resistances, R. Such a line may be called a "Line of constant E and R."

Let Fig. 3 represent such a line. Let i_0 and e_0 be the values of the current and potential before the field is applied. Then as the field is increased, let the current first decrease and then increase. The line $l'l''$ will be obtained, giving the relation between e and i produced by the increasing magnetic field. When the line stops at l'' the discharge becomes periodic. If the line $l'l''$ be continued it will intersect the axis of ordinates at P (see Fig. 3). Then OP will be equal to E, and we will have the relation

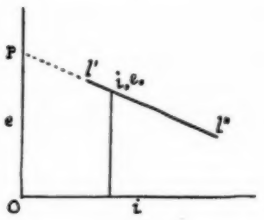

Fig. 3.

$$e = E - iR.$$

This is the equation of the straight line $l'l''$, and is equivalent to (1). This line has been called by Riecke[1] the "Verbindungslinie."

If we integrate (3) we get

$$i - i_0 = -\frac{1}{R}(e - e_0). \tag{4}$$

But e is a function of the strength of the magnetic field, H, and also of R. Therefore we may write $e = f(H, R)$, and (4) becomes

$$i - i_0 = -\frac{1}{R}(f(H, R) - e_0). \tag{5}$$

If the characteristic for the tube when no magnetic field is acting, is a rising characteristic, as it is, except for very small values of the current,[2] $f(H, R)$ will decrease as R increases, since an increase of R, if E is constant, will produce a decrease of e. Therefore $[f(H, R)]/R$ will decrease as R is increased, more rapidly than $1/R$.

Thus we see that the *variation of the current* $(i - i_0)$ will depend on the *variation of the potential* $(e - e_0)$ in the manner shown in (5). The sign of the current variation will always be opposite to that of the potential variation, and its magnitude will depend on the magnitude of the external resistance, R, decreasing as R increases. This variation of i with R for actual experimental values, is shown in Fig. 6.

Although the magnitude of the current variation when the magnetic

[1] Loc. cit., p. 597.

[2] See Ives, PHYS. REV., 9, p. 360, 1917, Fig. 7.

field acts on the tube depends on the magnitude of R, the volt-ampere characteristic for a tube subjected to a magnetic field of constant strength is not affected by variation in the external resistance, since a change in i, due to a change in R, will be counterbalanced by a change in e so that the point e, i, after the change in R, will lie on the same characteristic that it did before. This is a reasonable conclusion, and was found, by experiment, to be actually the case for the volt-ampere characteristic for $H = 157$ gausses, shown in Fig. 12. If, for a given pressure, the volt-ampere characteristics are drawn for several constant values of the magnetic field as in Fig. 12, the "line of constant E and R" is a straight line such as the dotted line in the figure, cutting these curves and connecting those points on them which have the same E and R.

5. EXPERIMENTAL RESULTS.

1. "*Lines of Constant E and R.*"—Three of these lines are shown in Fig. 4. They were obtained with tube B. When the magnetic field was

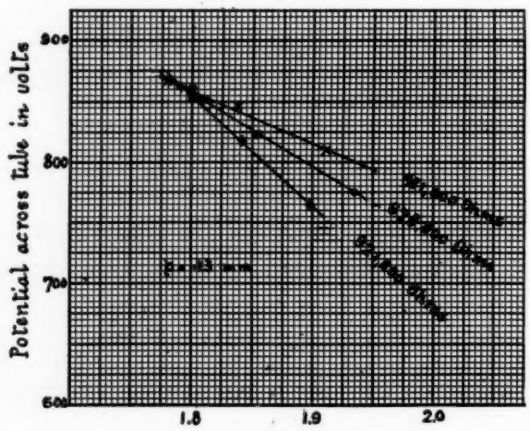

Fig. 4.

equal to zero, the current through the tube was 1.8 milliamperes, and the potential across it in each case, about 860 volts. As the field was gradually increased, the current first decreased to about 1.78 milliamperes and then increased to about 1.93 milliamperes, when the discharge became periodic. Each straight line represents a different external resistance, and a separate series of readings of current and potential. The magnetic field was varied from zero to about 157 gausses, the whole tube being acted upon by the field.

In Table I. are given the corresponding values of magnetic field, H, in

gausses; current, i, in milliamperes; and potential difference, e, in volts, for the three values of external resistance, R, in ohms.

no field and (*b*) with field of 157 gausses. It is seen that when the field is applied the striæ increase in number, fill the whole tube, and also appear on the side of the tube behind the cathode.

5. *Field Acting on Anode Only.*—To determine the effect on the region of the anode, the magnet was moved *up* until the bottom of the magnet was 4 cm. below the upper end of the tube. The ampere-gauss and the volt-gauss curves for this case, for Tube *C*, are shown in Fig. 9. The

TABLE I.

H.	$R = 481{,}000$.		$R = 678{,}000$.		$R = 921{,}000$.	
	i.	e.	i.	e.	i.	e.
0	1.800	858	1.800	854	1.800	852
80	1.780	867	1.800	861	1.792	863
118	1.838	847	1.854	824	1.841	819
157	1.911	810	1.935	775	1.898	765

It is interesting to note that we have here a method of measuring the external resistance in a circuit containing a battery, a high resistance and a discharge tube. For instance, the "lines of constant E and R" were plotted for external resistances of 132,000, 681,000 and 1,380,000 ohms,

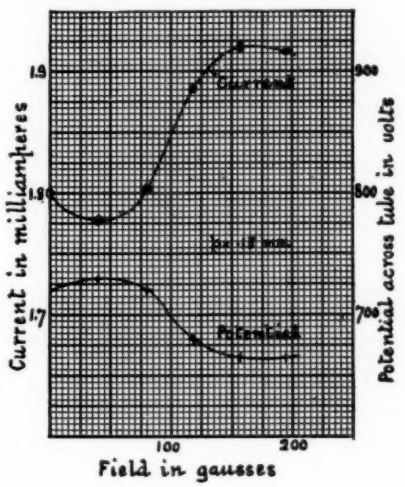

Fig. 5.

respectively. The values of these resistances as determined, in each case, by measuring the slope of the lines in volts/amperes, were 137,000, 685,000 and 1,300,000 ohms.

2. *Ampere-gauss and Volt-gauss Curves.*—The relation of the current to the field and of the potential to the field when the whole length of Tube *C* is subjected to an increasing uniform transverse magnetic field, and *E* and *R* are kept constant is shown in Fig. 5. It is seen that the current first decreases and then increases rapidly to a maximum value. At this maximum value the discharge becomes periodic. Readings of the milliammeter and electrometer after the discharge became periodic were not taken. The periodicity of the discharge was observed both with a rotating mirror and a telephone receiver in series with the tube. The potential across the tube varies, as we have seen that it must, in an opposite manner to the current.

3. *Effect of Magnitude of External Resistance on Shape of Ampere-gauss Curve.*—This is shown if we cause the magnetic field to act on the tube and gradually increase its strength. The current through the tube and the potential across it will vary so that they will be related to each other as shown in equations (4) and (5). The magnitude of the variation will depend on the magnitude of the external resistance, *R*. Three curves for the variation of the current with the field for three different values of *R*, 132,000, 681,000 and 1,380,000 ohms, respectively, are shown in Fig. 6. Tube *B* was used for these observations, and the

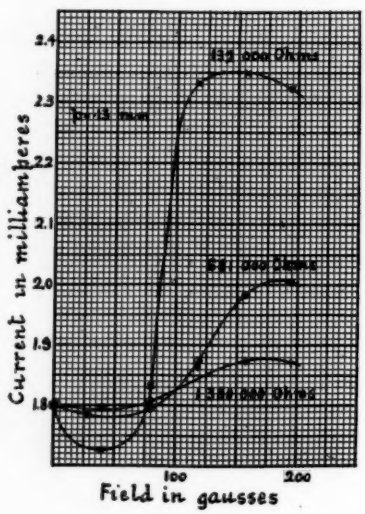

Fig. 6.

whole length of the tube was acted on by the field. It is seen that decreasing the value of the external resistance magnifies the curve. This was to be expected from equations (4) and (5).

4. *Force Acting on Cathode Only.*—To find the effect of the field on the

cathode only, Tube *C* being placed vertically, the anode above and the cathode below, the magnet was moved downwards until its top was only 2.8 cm. above the lower end of the tube. The curves shown in Fig. 7 were then obtained. The position of the tube with respect to the magnet

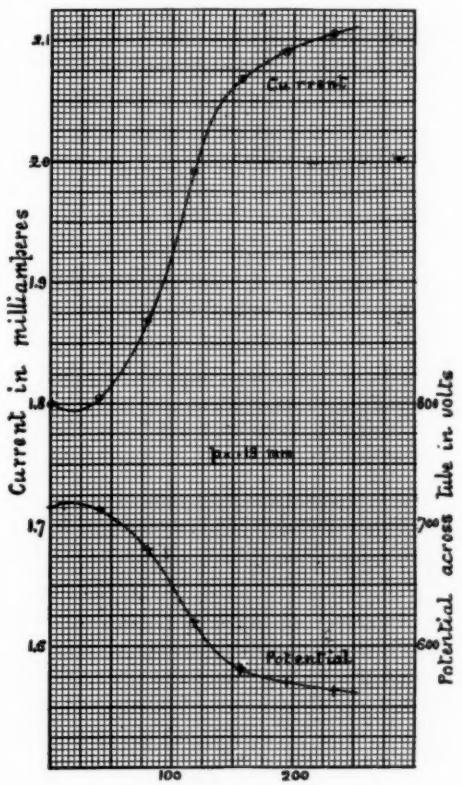

Fig. 7.

Field in gausses.

is shown in Fig. 8*a*, except that in this figure Tube *B* is shown in place, instead of Tube *C*. It will be noted that the curves are of the same form as those shown in Fig. 5, for the whole length of the tube exposed to the field, but that the current and potential variations are more than twice as great. To determine if the shape of these curves was affected to any extent by the stray field above the poles of the magnet, the magnet was still further lowered until its top was on a level with the lower end of the tube. A fresh series of measurements were made for the tube in this position. The results obtained were, within the accuracy of the experiment, like those of Fig. 7. The true values of the field above the poles of the magnet in this case were determined experimentally and

these values used in plotting the curves. In Fig. 8 are shown representations of the appearance of the discharge through Tube *B*, (*a*) with position of the tube with respect to the magnet is shown in Fig. 10*a*, except that in this figure Tube *B* is shown in place instead of Tube *C*. It will be observed that the curves are entirely different from those for the cathode and are straight lines, showing that when the field acts on the region of the anode the current decreases as the field increases and, that the decrease of the current is directly proportional to the strength of the field. In Fig. 10 is shown the appearance of the discharge, through Tube *B* (*a*) with no field and (*b*) with the field of 241 gausses.

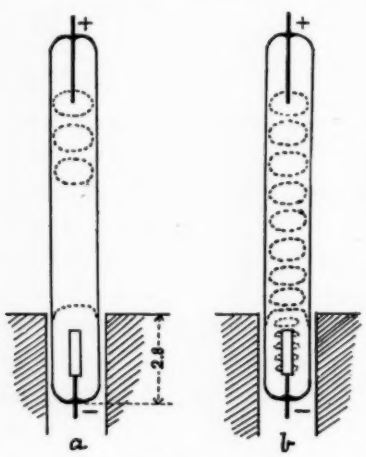

Fig. 8.

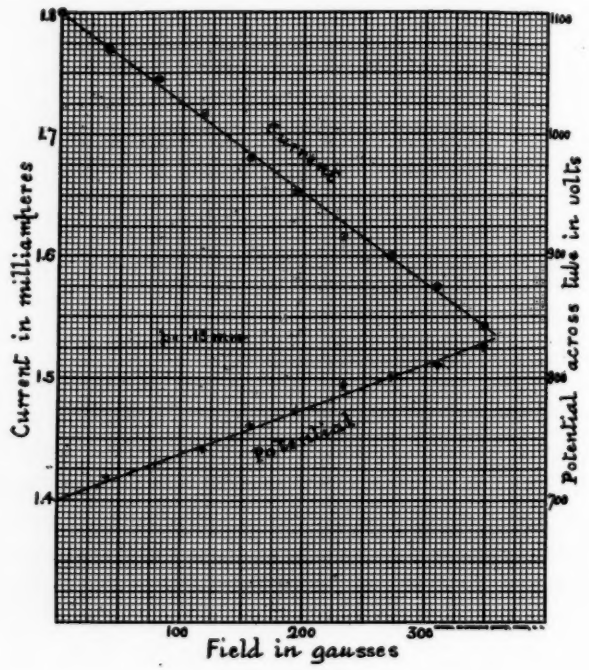

Fig. 9.

6. *Volt-ampere Characteristics for Magnetic Fields of Different Strengths.* —Preliminary experiments to determine the volt-ampere characteristics

for zero field and a field of 41 gausses were made with Tube *A*. The results are shown in Fig. 11. The field was applied to the whole length of the tube. They are very similar to those obtained by Riecke and show that the characteristics for fields greater than zero cross the characteristic for zero field; for the smaller values of the current, they lie above the characteristic for zero field and for larger values, below it.

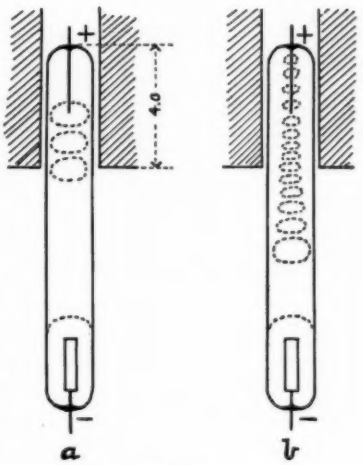

Fig. 10.

The volt-ampere characteristics found for Tube *B*, for zero field and for fields of 40, 118 and 157 gausses, respectively, are shown in Fig. 12. They were obtained by first determining the characteristic for zero field, and then finding the increase, or decrease, of the current and potential, when a

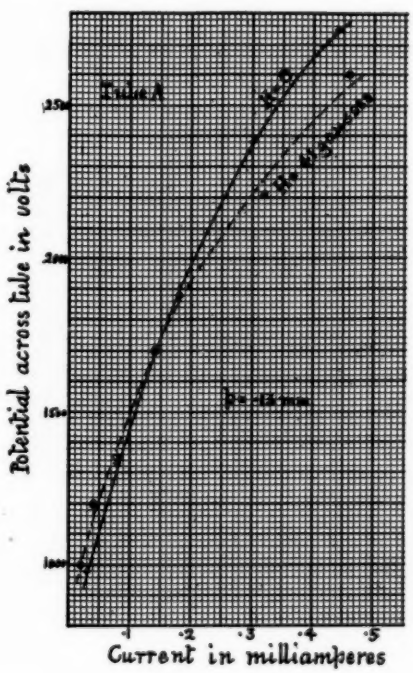

Fig. 11.

given field was applied, for a number of points on it. They are of the

same general form as those given by Riecke.[1] The dotted line, shown in Fig. 12, is a line of constant E and R.

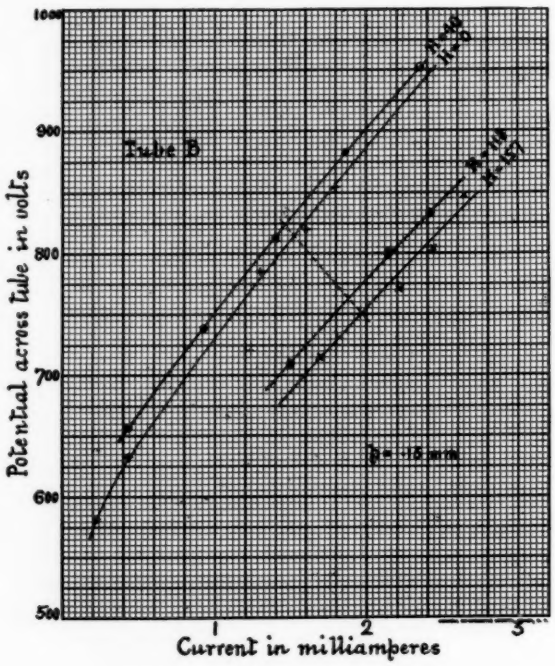

Fig. 12.

6. Discussion of Results.

It will be seen from Figs. 5, 7 and 9, that, to a first approximation, the effect of the field acting upon the whole tube is the *sum* of the effects obtained when acting upon the cathode and anode regions separately.[2] It will also be seen that the action of the field upon the cathode region is, in the main, to greatly increase the current, whilst its effect upon the anode region is always to decrease it. The curves given are only three out of a great many obtained which all show the same general character. The curves for the cathode region all show a slight decrease for small fields and then a very large increase for greater fields, reaching a maximum value at which the discharge becomes unstable. The curves for the anode region are all straight lines. For the curves of Figs. 5, 7 and 9 the external resistance was of graphite and had a value of 481,000 ohms. In Fig. 7, for field acting on cathode region only, the decrease in current for small values of the field was very carefully investigated. I was

[1] Loc. cit.

[2] See Stark, Elektrizität in Gasen, 1902, pp. 408, 409.

rather skeptical of its existence, but very careful measurements showed that there was a small decrease for small values of the field. It was also found to exist when the magnet was moved down so that its top was on a level with the lower end of the tube. It is probably due to the influence of the weak field outside the poles of the magnet on the Faraday dark space or on the lower end of the positive column.

Stark,[1] in the paper referred to above, has given curves showing the effect of a transverse magnetic field on the cathode fall. It is to be noted that Stark's investigation deals with the cathode fall alone and not with the fall between the cathode and anode. In his paper he plots the relation between the cathode fall and the magnetic field, but not between current and field. The curve given in Fig. 11 of his paper, for a pressure of .163 mm., agrees very closely in form with the volt-gauss curve I have given in my Fig. 7 except that his curve does not show a small increase of potential for small fields. If we plot the values of the current given by him, we get a curve very similar to my current curve of Fig. 7. A plot of Stark's values both for current and potential is given in Fig. 13. The fact that Stark's values do not show a decrease of

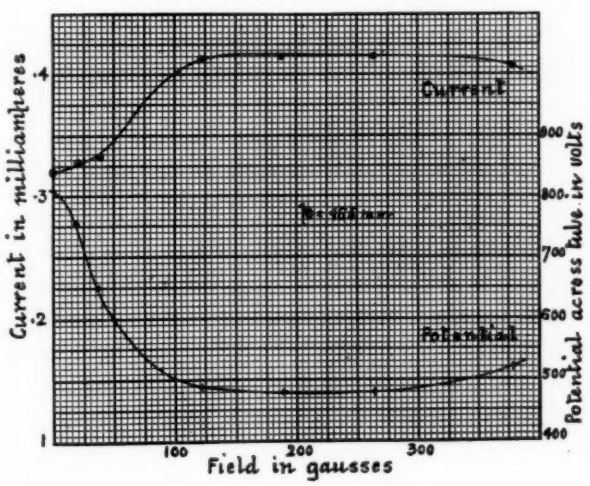

Fig. 13.

the current for small values of the field tends to support the theory that in my results this decrease was due to the action of the weak external field on the Faraday dark space, or on the lower end of the positive column.

Aside from the small decrease of the current for small fields, Fig. 7 reminds one, for a considerable part of its length, of the curves given by

[1] Loc. cit., pp. 43–45.

Townsend[1] in his Theory of Ionization by Collision of Negative Ions, for increase of current due to increase of length of path. I think we may assume that the ascending part of the current curve, from the point where it cuts a line parallel to the axis of abscissas to its point of inflexion, is due to an increase in the length of the path travelled by the electrons under the action of the magnetic field. As pointed out by Stark,[2] a transverse magnetic field will increase the ionization in two ways, (1) by increasing the length of the path, and (2) by concentrating it, by holding the electrons in the neighborhood of the cathode. Both of these causes would act like an increased length of path. In the upper part of the curve, from the point of inflexion to the point where it becomes horizontal and the discharge becomes unstable, besides the action increasing the length of path of the electrons, another action of the field enters in. After the field reaches a certain strength, a retarding effect of the field begins to appear due to its taking the electrons prisoners and causing them to revolve continually around the lines of force or else to travel along them to the walls of the tube. If this is so, the current through the tube should first increase, with increasing field, after a while reach a maximum value and then begin to decline in value. The curve shown in Fig. 7 indicates that the current is approaching such a maximum when it becomes unstable. This maximum is shown by Stark's values in Fig. 13.

The linear decrease of the current when the *anode region* is exposed to a transverse magnetic field, may perhaps be explained by the fact that the length of the positive column is increased by the action of the field. This increase of length is shown in Fig. 10*b*. It is seen there that the effect of the field is to press the positive column away from the observer, at the same time causing its upper end to move along the wire forming the anode towards the upper end of the tube. If the potential difference across the electrodes increases as the length of the positive column increases, its change of length, in this case, might produce the change of potential shown in Fig. 9. Another cause for the reduced current, under the action of the field, may be the decreased cross-section of the positive column. Also it is possible that the transverse magnetic field deflects some of the negative carriers so that they do not reach the anode, and that the number deflected is proportional to the strength of the field.

The fact that the effect of the transverse magnetic field is different, according as it is applied at the anode or cathode, raises the question "Are the negative carriers of the same nature in the cathode glow, as in

[1] Electricity in Gases, 1915, pp. 266, 267.

[2] Ann. Phys., 12, p. 34, 1903.

the positive column?" Skinner[1] has come to the conclusion, from his own experiments on electrode polarization and those of Chrisler on anode absorption, that in general the negative carriers in the positive column are atoms and "that the electrons must become largely attached to the atoms after leaving the negative glow." H. A. Wilson[2] in his experiments on the Hall effect found that the difference between the velocities of the negative and positive ions was large in the striæ and small in the dark places between them. He suggests that electrons are produced largely in the striæ and that by the time they get into the dark spaces they have become attached to "molecules."

In my experiments on the so-called Magnetic Rays of Righi,[3] I found that the Righi effects were not produced if the transverse magnetic field acted only on the positive column. To get them it must act on the negative glow. That is, the negative carriers in the positive glow do not follow the lines of the magnetic force as they do in the negative glow. This result apparently shows that in the positive glow the negative ions, if of the same nature as those in the negative glow, do not move with as great a velocity, since Thomson has shown that for the ions to follow the lines of magnetic force the product of their velocity and the strength of the magnetic field must be large.[4]

Wellisch[5] from his researches on air ionized by polonium comes to the conclusion that in air the negative carriers are both ions and electrons, and that at a pressure of .15 mm. the ions form more than 50 per cent. of them. He also concludes that the ions have a definite mass which does not vary with the pressure.

Fulcher[6] and Gehrcke and Seeliger[7] have shown that the color of the light emitted from a glow discharge depends upon the velocity of the electrons; the bluish light being produced by the fast-moving, and the reddish by the slow-moving electrons. So that it is possible that all the light in the Geissler discharge, both of the positive glow and of the negative glow may be produced by electrons.

The weight of the evidence, at the present time, seems to be in favor of the view that the ionization in the positive column is produced by electrons, and that the difference in the behavior of the positive glow and the negative glow under the action of a magnetic field is due to the lower velocity of the electrons in the positive glow.

[1] PHYS. REV., 9, 314, 1917.
[2] Loc. cit.
[3] PHYS. REV., 9, 354, 1917.
[4] See Thomson, Conduction of Electricity through Gases, second edition. 1906, p. 105.
[5] Am. Jour. Sci., 39, 583–599, 1915.
[6] Astro. Phys. Jour., 34, 388, 1911; 37, 60–71, 1913.
[7] Verh. Deutsch, Phys. Gesell., 10, 335, 1912.

When the whole length of the tube, shown in Fig. 1, is subjected to a transverse magnetic field and a current of 1.8 milliamperes passes through it, the negative and positive glows behave very differently. The negative glow, or at least that portion of it bounding the Crookes dark space, is not sensibly changed in position by the strongest field that can be applied, whereas the positive glow is extraordinarily modified. The number of striæ is increased from 3 to 17; each stria is reduced to a fraction of its former length, is much reduced in width and is flattened against one side of the tube, and the striated positive column extends from the anode right up to the negative glow.[1] The positive column acts like a flexible metallic conductor.

In the experiments described in this paper the positive column was always striated, there being usually three striations present for zero magnetic field. At the pressure used, .13 mm. Hg, the condition of striation is a condition of stable discharge, *i. e.*, the discharge is only continuous when the column is striated. As the field is increased from zero, the discharge stays continuous until it reaches a value of about 300 gausses, when it becomes periodic. If the field is still further increased, a value is reached where no discharge at all passes. This action of the field in stopping the discharge periodically does not depend on lowering or raising the potential difference across the tube, since, when the field is applied at the cathode, the discharge ceases when the potential is *lowered* to about 560 volts, and when applied at the anode, ceases when the potential is *raised* to about 830 volts. The peculiar behavior of the positive column being the same in both cases, the striæ being increased in number, shortened in length and pressed against the side of the tube, suggests that the instability of the discharge when the field reaches a certain strength may have something to do with the decrease in the cross-section of the positive column or with the properties of the striæ.

A peculiar property of the Geissler tube discharge has been observed by Reiger.[2] He found that such a discharge may be continuous in one part of the tube, and discontinuous in another part, at one and the same time. I observed the same thing while performing the experiments described in this paper when the whole length of the tube was subjected to the magnetic field, and the field was of about the strength which made the discharge periodic. The striated positive column extended from the anode to the cathode glow, was pressed against the side of the tube, and had 16 or 17 striæ. As the field was increased the striæ at the middle

[1] See Ives, PHYS. REV., 9, pp. 350, 351, 1917.

[2] Sitzber. d. Phys. Med. Soc. in Erlangen, 37, 1–130, 1905.

of the tube disappeared first. Using a rotating mirror, it could be seen that the discharge in this part of the positive column was discontinuous, while it was continuous throughout the rest of the tube. Since the mean current must be the same through every cross-section of the tube, this condition, apparently, can only exist if a certain portion of the tube acts as a condenser, periodically storing up a charge, and then discharging it slowly through the rest of the tube, which acts as a high resistance.[1] The phenomenon was particularly striking and significant when the field acted on the anode region only and the striæ differed in width and length as shown in Fig. 10*b*. In this case, it was observed that the discharge became discontinuous only in the narrow part of the column where the field was strong and the striæ narrow and close together. The striations at the lower end of the column, near the cathode, remained intact until the discharge ceased altogether.

I have already stated that, when the magnetic field, applied at the cathode, was gradually increased, new striæ appeared at the anode and those already in existence moved down towards the cathode so that the distance between the negative glow and the first stria gradually decreased. This behavior of the striæ under the action of the field, may, I think, be explained in this way: Stark's results and my own show that the effect of the field is to lower the cathode fall of potential. This decrease of the cathode fall will produce a decrease in the free positive charge in the Crookes dark space, and this in turn will increase the strength of the field in the Faraday dark space, so that the first stria will move a certain distance towards the cathode.

A possible explanation of the action of a magnetic field in making the discharge periodic is suggested by the remarkable results obtained by Thomson[2] for the striations when the discharge is produced by a Wehnelt cathode. He found that in this case the electric field in the dark spaces between the striations actually became *negative*, so that the ions traversing a dark space and moving against the force, must have had a sufficient initial velocity to carry them across the space. Now, very little is known about the effect of a transverse magnetic field on the difference of potential across the ends of a positive column,[3] or upon the electric field in this column. However, Willows'[4] results show a very decided lowering of the electric field in the positive column under the action of a magnetic field. Suppose, now, that in the experiments described in my present paper, when the magnetic field is gradually made stronger and

[1] For such a discharge, see Fulcher, Astrophys. Journ., 33, p. 56, 1910.

[2] Phil. Mag., 18, 441–451, 1909.

[3] See Ives, loc. cit., p.355, Table II.

[4] Loc. cit., p. 258, Fig. 7.

stronger the maxima and minima of the electric field, corresponding to the bright and dark parts of the striations, still persist, but that the minima decrease in value until the undulating curve representing the electric field cuts the x axis. We would then have a curve similar to that given by Thomson, in Fig. 1 of his paper. If the depression of the curve still further continued as the magnetic field was further increased, a value of the magnetic field would be reached where the negative field in the dark spaces would become so strong that the ions could no longer get across them, and the discharge in that part of the tube would be interrupted. Such an action would, it appears to me, suffice to produce the effects observed. Whether there is such a distribution of the electric field in the present case can only be determined by a series of measurements of its strength in the positive column as the magnetic field is gradually increased.

7. SUMMARY.

1. In a discharge tube, 1.5 cm. in diameter, with the electrodes 7.5 cm. apart, containing air at a pressure of .13 mm. and carrying a current of 1.8 milliamperes, the effect of a transverse magnetic field upon the discharge, when acting on the cathode region only, is to increase the current through the tube; when acting on the anode region only, to decrease it; and when acting on the whole tube, to increase it.

2. The ampere-gauss curve for the field acting on the cathode region only is a modified exponential curve of the form obtained by Townsend for increasing length of path.

3. The ampere-gauss curve for the field acting on the anode region only is a descending straight line.

4. The ampere-gauss curve for the field acting on the whole tube is, to a first approximation, the sum of the curves for field acting on cathode region only and for field acting on anode region only.

5. When a magnetic field acts on a tube, the external variables of its circuit being kept constant, the potential across the tube and the current through it vary oppositely, one decreasing when the other increases according to the law

$$e = E - iR,$$

where e is the potential across the tube; i, the current through it; E, the impressed electromotive force and R the external resistance of the circuit. If the potential is plotted as a function of the current, we get a straight line, whose slope is equal to R, passing through the point E on the axis of ordinates. Such a line may be called a "Line of constant E and R."

6. The amplitude of the ampere-gauss or the volt-gauss curve is affected by the value of the external resistance, R, of the circuit; the amplitude of the ampere-gauss curve being decreased by increasing R, and that of the volt-gauss curve, increased.

7. The volt-ampere characteristics of the tube were determined for magnetic fields of different strengths. The characteristic for a magnetic field of a given strength crosses the characteristic for zero field at a certain critical value of the current, which differs for different values of the field. For values of the current less than the critical value, the current is increased by the field, for values greater, decreased.

CLARK UNIVERSITY,
WORCESTER, MASS.,
February 18, 1918.

ON THE DIFFRACTION OF LIGHT BY AN OBLIQUELY HELD CYLINDER.

BY T. K. CHINMAYANANDAM.

1. INTRODUCTION.

THE problem of the diffraction of light by a transparent cylinder, on which plane waves are *normally* incident, has been treated by many writers,[1] both with respect to the classical wave theory, and from the fundamental electro-magnetic equations, the problem having special application to the theory of the rainbow. The writer has observed some very interesting phenomena, which are exhibited when the light falls *obliquely* on the cylinder, and which do not seem to have been previously described. It is proposed in this paper to give an account of the phenomena, and to attempt a theoretical explanation.

If light falls on a transparent cylinder normally, the rays that emerge after refraction and one internal reflection form, as is well known, two parallel caustics whose directions make a definite angle, which, for glass, is about 45°. If the incidence of light on the cylinder is made oblique, the two caustics are found to approach each other more and more closely. At a certain angle of incidence (about 50°, for glass), the two caustics of the emergent rays coalesce, and absolutely cease to exist for greater angles of incidence. At and near the stage where the caustics and the supernumerary fringes, which accompany them, coalesce, the phenomena presented are of particular interest, and may be studied by mounting the cylinder horizontally on the table of a spectrometer. The collimator slit should also be made horizontal, and may be illuminated by the electric arc or by a Cooper-Hewitt lamp. With this arrangement, we can observe visually or photograph the phenomena corresponding to varying angles of incidence simultaneously. Fig. 1 reproduces a photograph of the effects thus observed in monochromatic light. If part of the length of the horizontal slit of the collimator be covered up, so as to leave only a short

[1] For detailed references to the earlier work by Airy, Mascart, Pernter, Miller, Pulfrich, and others, see a paper by Aichi and Tanakdate on the "Theory of the Rain-bow, Due to a Circular Source of Light," Journ. of the Coll. of Sc., Imp. Univ. of Tokyo, Vol. XXI., Art. 3 (1906). Among recent references, may be mentioned Debye, Phys. Zeitschr., 9, Nov., 1908, also Sc. abstracts, 1909, p. 88, and Mobius "On the Theory of the Rain-bow," Ann. der Phy., 33 (1910), and 40 (1913). See also Potzger on "Diffraction in the Ultra-microscope," Ann. der Phys., 30 (1909).

opening, the phenomena corresponding to any particular angle of incidence are observed in the field. In the photograph shown, they would correspond to a narrow strip perpendicular to the bisector of the angle between the two bright caustic lines.

The interesting feature of the diffraction pattern, which distinguishes it from the fringes in the rainbow, is that the two systems of caustic fringes, which are far apart in the case of normal incidence, overlap and interfere with each other when the incidence is oblique, giving rise to a beautiful structure in the fringe-system, especially near its termination, where the caustics meet and vanish. As the angular separation of the caustics increases, the overlapping of the fringes becomes less and less perceptible in white light, but a few fine interference fringes, which form practically a separate system, may be seen midway between the caustics; with the spectrometer, these are visible even at an incidence nearly normal to the cylinder, if its diameter is about 0.5 mm. or less. When the diameter of the cylinder is of the order of 0.01 mm., these fringes become broad and bright. In this case, the caustics and their supernumeraries are practically achromatic, but the system of interference fringes seen midway between the caustics is strongly colored, except, of course, the central fringe which is white. Figs. 2 (*a*, *b*, and *c*) represent the phenomena observed with a glass fiber of that diameter, and correspond respectively to three different angles of incidence.

2. GEOMETRICAL THEORY.

Let the axis of the cylinder be the z-axis, the incident rays being parallel to the xz-plane. The direction cosines of the incident ray may be taken to be (l, o, n), and the point of incidence of any ray on the cylinder may be represented by the cylindrical coördinates $(a\cos\varphi, a\sin\varphi, z)$, a being the radius of the cylinder. Also let the direction cosines of the refracted ray, the internally reflected ray, and the emergent ray be respectively (l', m', n'), (l'', m'', n''), and (λ, μ, ν). Then we shall have, for the first refracted ray, from the fundamental laws of refraction,

$$\begin{vmatrix} l, & o, & n \\ \cos\varphi, & \sin\varphi, & o \\ l', & m', & n' \end{vmatrix} = 0. \tag{1}$$

and

$$1 - l^2\cos^2\varphi = \mu^2\{1 - (l'\cos\varphi + m'\sin\varphi)^2\}. \tag{2}$$

and we shall have two similar pairs of equations for the other two rays. Solving equations (1) and (2), we get

$$\left.\begin{aligned} l' &= -k\cos\varphi + \frac{l}{\mu}\sin^2\varphi \\ m' &= -k\sin\varphi - \frac{l}{\mu}\sin\varphi\cos\varphi \\ n' &= \frac{n}{\mu} \end{aligned}\right\}, \qquad (A)$$

where

$$k^2 = 1 - \frac{1}{\mu^2}(1 - l^2\cos^2\varphi). \qquad (3)$$

If this refracted ray meets the surface of the cylinder at a point φ', we have

$$\frac{\cos\varphi' - \cos\varphi}{l'} = \frac{\sin\varphi' - \sin\varphi}{m'}, \qquad (4)$$

from which, using equations (A), we can deduce the relation

$$\tan\frac{\varphi - \varphi'}{2} = \frac{k\mu}{l\sin\varphi}. \qquad (5)$$

Similarly, if the point of emergence of the ray from the surface of the cylinder has the coördinate φ'', it can be shown that

$$\tan\frac{\varphi' - \varphi''}{2} = \frac{k\mu}{l\sin\varphi} = \tan\frac{\varphi - \varphi'}{2} \qquad (6)$$

and also that

$$\left.\begin{aligned} l'' &= -k\cos\varphi' + \frac{l}{\mu}\sin\varphi\sin\varphi' \\ m'' &= -k\sin\varphi' - \frac{l}{\mu}\sin\varphi\cos\varphi' \\ n'' &= \frac{n}{\mu} \end{aligned}\right\} \qquad (B)$$

and

$$\left.\begin{aligned} \lambda &= l\cos(\varphi + \varphi'') = l\cos 2\varphi' \\ \mu &= l\sin(\varphi + \varphi'') = l\sin 2\varphi' \\ \nu &= n \end{aligned}\right\}. \qquad (C)$$

Equations (C) determine the direction of the emergent rays. If the radius of the cylinder is very small, we can regard, as an approximation, that the rays all start from the origin o itself. Then the emergent rays will lie on the cone

$$x^2 + y^2 = \frac{l^2}{n^2}z^2. \qquad (5)$$

They would be parallel when

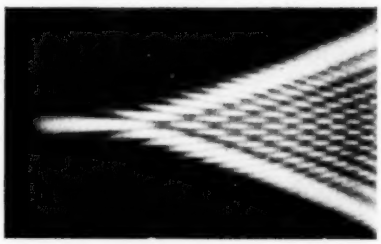

Fig. 1.

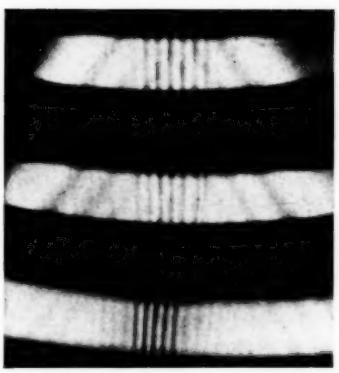

Fig. 2.

T. K. CHINMAYANANDAM.

$$\frac{d\lambda}{d\varphi} = 0, \qquad \frac{d\mu}{d\varphi} = 0,$$

which reduce to the condition that

$$\frac{d\varphi'}{d\varphi} = 0.$$

From (4), we have,

$$\cos(\varphi - \varphi') = \frac{l^2 \sin^2 \varphi - \mu^2 k^2}{\mu^2 - 1 + l^2},$$

$$\sin(\varphi - \varphi') = \frac{4l^2 \sin \varphi \cos \varphi}{\mu^2 - 1 + l^2}, \qquad \text{since } \frac{d\varphi'}{d\varphi} = 0$$

$$= \frac{2\mu k l \sin \varphi}{\mu^2 - 1 + l^2} \qquad \text{by (4).}$$

Hence

$$\cos \varphi = \frac{\mu k}{2l}$$

or by (3),

$$\cos^2 \varphi = \frac{\mu^2 - 1}{3l^2}. \tag{6}$$

If the incidence is normal, $l^2 = 1$ and equation (6) reduces to

$$\cos^2 \varphi = \frac{\mu^2 - 1}{3}, \tag{7}$$

which is the condition for crowding of the emergent rays from a rain-drop. It is also seen from (6) that φ will be imaginary, if $l^2 < (\mu^2 - 1)/3$, which happens for glass if the angle of incidence is greater than about 50°. The caustics, therefore, cease to exist at very oblique incidence.

The actual direction of the emergent rays, where they are parallel, *i. e.*, the direction of the cuastics may now be determined.

$$\cos 2\varphi' = \cos\{2(\varphi - \varphi') - 2\varphi\}$$

$$= \frac{1}{(\mu^2 - 1 + l^2)^2}\left\{12l^2 s + 3s^2 - l^4 + \frac{2s^3}{l^2}\right\} \tag{8}$$

from equations (4) and (6), s being written for $(\mu^2 - 1)/3$. The directions of the two caustics are thus given by

$$\left.\begin{aligned} \lambda &= \quad l \cos 2\varphi' \\ \mu &= \pm l \sin 2\varphi' \\ \nu &= n \end{aligned}\right\},$$

where φ' is determined by (8). The angle between these two directions is given by

$$\cos \epsilon = 1 - 2l^2 \sin^2 2\varphi'.$$

The results of a few measurements of the angular separation of the caustics, at varying angles of incidence, are given below, with the corresponding values calculated from theory. The experimental arrangement used was simply to have the cylinder mounted on the table of a spectrometer, making the collimator slit short and narrow. The electric arc was used with a green ray filter for illuminating it. The angle of incidence was measured, as usual, by setting the cross-wire of the telescope on the reflected image of the slit, and then taking the direct reading. The angle between the caustics was determined by reading off the linear separation in cm. of the caustics, on a screen held at a distance of one meter from the cylinder, and dividing it by 100. The refractive index of the cylinder was measured by dipping it in a rectangular glass cell, illuminated by green light and containing Thoulet's solution.[1] The liquid, whose refractive index could be continuously varied by mixing water, was diluted until the shadow of the cylinder became practically invisible. The chief difficulty in the experiment was the selection of the cylinder itself. Most of the large number of glass threads that were examined gave somewhat irregular effects, a slight rotation of the cylinder about its own axis changing the angle between the emergent caustics very much. The irregularities are apparently due to the cylinder being not quite circular, *i. e.*, to slight ellipticity in its cross-section. Considering the fact that even a slight ellipticity in the cross-section of the cylinder affects the results appreciably, the agreement between the observed and calculated values is good. As was anticipated from theory from equation (7), the caustics cease to exist after a critical angle of incidence, which is about 50° here.

TABLE I.

Angle of Incidence.	Angular Separation of the Caustics.	
	Observed.	Calculated.
32° 15′	17° 12′	17° 48′
35° 15′	13° 42′	13° 47′
38° 15′	10° 30′	10° 0′
41° 15′	6° 54′	7° 18′
44° 15′	3° 42′	3° 12′
47° 15′	1° 12′	1° 50′
49° 39′	0°	0°
52°		

($\mu = 1.51$).

[1] See R. W. Cheshire, Phil. Mag., Oct., 1916.

3. Form of the Emergent Wave-surface.

Passing on now to consider the phenomena in the light of the wave theory, we have first to determine the form of the wave on emergence from the cylinder. Figs. 3 and 4 represent the projection of the wave

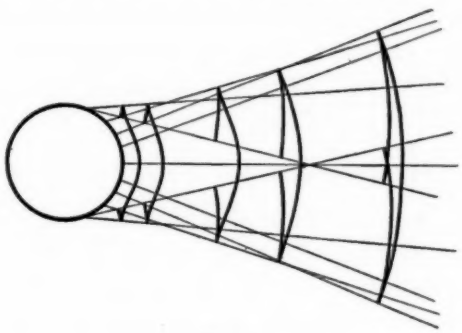

Fig. 3.

front on the plane passing through the two caustics, Fig. 3 illustrating the case of normal incidence, and Fig. 4, the case when the incidence is about 50°, the angle between the caustics being then almost zero; they have been drawn by plotting out a number of emergent rays with data calculated from the formula in section 2 above, and drawing curves normal to them. It will be seen that the section of the emergent wave has two points of inflection on either side of the central line, and at a

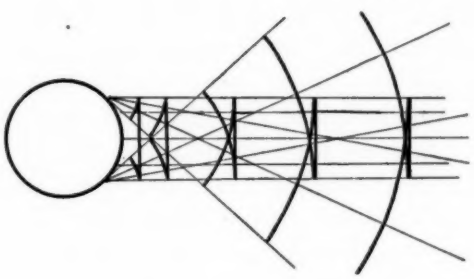

Fig. 4.

great distance from the cylinder, the disturbance at any point may be regarded as due to the interference of three sets of wave trains, to which the emergent cusped wave gives rise. In a direction close inside either of the caustics, the effect of one of the wave-trains is negligible in comparison with that of the other two, and the problem of determining the illumination in any direction is then the same as in the case of the rainbow, which has been worked out by Airy, Mascart, and others. But the

approximation suggested is not valid in directions nearly midway between the caustics, even when the latter are widely separated, and is totally inapplicable when the caustics make only a small angle with each other. This is evident on an inspection of Fig. 1. At a sufficient distance from the "tail" of the pattern, the caustics are widely separated and the fringe system is much like the supernumerary fringes in the rainbow, except near the central line where, as already explained, some interference fringes are observed. But near the "tail," a peculiar criss-cross structure is observed in the fringe-system.

4. Calculation of the Intensity of Illumination.

It follows from equation 5 in section 2 above that the emergent wave may be regarded approximately as spreading on the surface of a cone, whose axis coincides with that of the cylinder. But if the angular separation of the caustics is small, we can make a further approximation and regard the wave as spreading entirely on planes parallel to that passing through the two caustics. The section of the wave-front by that plane may, in effect, be considered to be a symmetrical curve of the form ODO' shown in Fig. 5, with two inflection points O, O' on either side, the normals at those two points indicating the direction of the emergent rays where they are parallel. In any direction inclined at a small angle θ to one of the normals, it is apparent from the figure that there are three rays originating at three different points a, b, c on the emergent wave. We can consider the effect at any point in the direction θ as due to the interference of these three rays emerging from the wave-front in that direction. We can, for simplicity, regard the amplitude of disturbance to be the same at all points on the emerging wave surface itself. Then the amplitudes of the three rays which proceed in the direction θ, will, at a great distance from the cylinder, be proportional to the square roots of the radii of curvature of the wave ODO' (Fig. 5) at the points a, b, c from which they respectively originate. We have next to calculate the path difference of each pair of these rays, and then the illumination at a point can be easily calculated.

A simple method of analytically representing the curve ODO' suggests itself. The curve may be regarded as two curves OD, DO' fitted up to form one continuous curve, the equation to the former being

$$y_1 = Ax_1^3$$

with respect to O, the inflection point, as origin, and the inflectional tangent OX_1, and normal OY_1 as axes of reference, and the equation to the latter being

$$Y_2 = Ax_2^3$$

with respect to O' as origin, and the inflectional tangent and normal at that point as axes of reference. The curves are considered as extending to infinity on the positive side of x, but are obviously limited on the negative side by the central line CC'.

Consider first the rays that start out from the points a and b. The amplitudes of the disturbances due to them are by symmetry equal, and will be proportional to a_1 where

$$a_1^2 = 1 \Big/ \frac{d^2y}{dx^2} = 1/6Ax = \pm\, 1/6A \left(\frac{\theta}{3A}\right)^{1/2}.$$

Taking into account the gain in phase of $\pi/2$ (indicated by the negative sign) of one of the rays, which passes through a focus, we find that the amplitude of either ray is

$$a_1 = (12A\theta)^{-1/4}. \tag{9}$$

The phase difference between the two rays can be shown to be equal to

$$\frac{2\pi}{\lambda}\left[\tfrac{4}{3}\theta\left(\frac{\theta}{3A}\right)^{1/2}\right] - \frac{\pi}{2}. \tag{10}$$

The amplitude of the resultant of the two will be

$$a_2 = 2(12A\theta)^{-1/4} \cos\left\{\frac{\pi}{\lambda}\cdot\tfrac{4}{3}\theta\left(\frac{\theta}{3A}\right)^{1/2} - \frac{\pi}{4}\right\} \tag{11}$$

and its phase will be $[-(\pi/4)]$ with respect to the ray from the center O in the same direction. We have now to determine the amplitude a_3 of the ray from the point c, and its phase δ with respect to the resultant of the first two rays. If the angle between Oy_1 and $O'y_2$ be denoted by 2α,

$$a_3 = \{12A(2\alpha - \theta)\}^{-1/4}. \tag{12}$$

The perpendicular from O on the tangent to the curve DO' at the point c can be shown to be

$$\frac{1}{\{1+(2\alpha-\theta)^2\}^{1/2}}\left[2(2\alpha-\theta)\left(\frac{\alpha}{3A}\right)^{1/2} - \alpha\left(\frac{\alpha}{3A}\right)^{1/2} + \tfrac{2}{3}(2\alpha-\theta)\left(\frac{2\alpha-\theta}{3A}\right)^{1/2}\right]$$

$$= \left(\frac{\alpha}{3A}\right)^{1/2}(3\alpha - 2\theta) + \tfrac{2}{3}(2\alpha - \theta)\left(\frac{2\alpha - \theta}{3A}\right)^{1/2} \quad \text{(approx.)}.$$

Hence, allowing for the gain in phase of $\pi/2$ of the third ray in passing through a focus, we get

$$\delta = \frac{2\pi}{\lambda}\left[\left(\frac{\alpha}{3A}\right)^{1/2}(3\alpha - 2\theta) + \tfrac{2}{3}(2\alpha - \theta)\left(\frac{2\alpha - \theta}{3A}\right)^{1/2}\right] - \frac{\pi}{4}. \tag{13}$$

The illumination in the direction θ is then given by

$$I = a_2^2 + a_3^2 + 2a_2a_3 \cos\delta \tag{14}$$

a_2, a_3 and δ being determined by equations (11), (12) and (13).

Illumination Outside the Caustics.—It is seen from (11) that a_2 becomes infinite when $\theta = 0$, and also that the above theory is inapplicable when θ becomes negative. For, outside the caustics, it is apparent that there is only one ray which emerges in any given direction. But, since the emergent cone of light is abruptly terminated in the direction $\theta = 0$, we must also take into account a diffraction effect, similar to that within the geometrical shadow of a straight edge. According to Sommerfeld's well-known investigation,[1] this effect can be represented by that due to a single radiating source placed at the edge, *i. e.*, at O (Fig. 5) in our

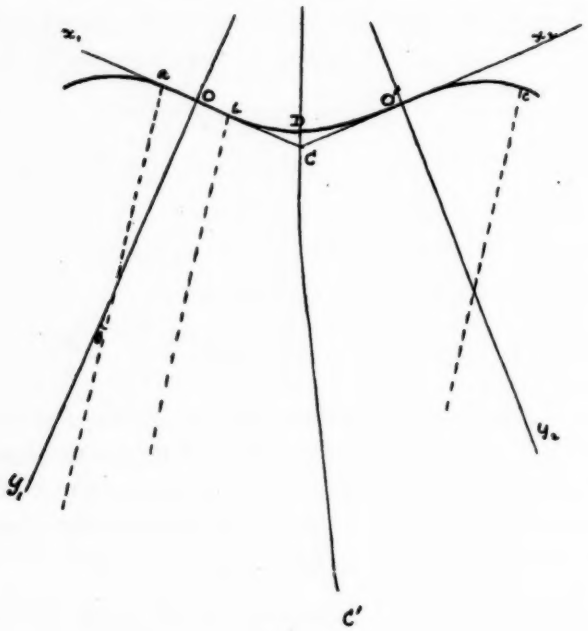

Fig. 5.

problem. Since the whole effect is small, we can consider approximately that the diffracted ray is of the same amplitude as the ray which emerges in the same direction from the other half of the wave-front. The illumination curves, outside the caustics, have been actually drawn on this assumption, the curves being rounded off at the point corresponding to $\theta = 0$.

The value of the constant A can be calculated approximately by equating the length OD (Fig. 5) to $(a \sin \varphi'')$, where φ'' corresponds to the point of emergence of the caustic from the surface of the cylinder. Thus we shall have

[1] Sommerfeld, On the Math. Theory of Diffraction, Math. Annalen, Vol. XLVII., p. 317 (1895).

$$\left(\frac{\alpha}{3A}\right)^{1/2} = a \sin \varphi'' \text{ (approx.)}. \qquad (15)$$

The intensity of illumination has been calculated on the above theory for different values of θ and the illumination curves, for the cases when the angle between the caustics (2α, approximately) is (1) 0° 56′, (2) 1° 52′, are shown in Fig. 6.[1] A comparison of the curves with the photograph (Fig. 1) shows that the theory is capable of explaining the facts very closely. To make the comparison quantitative, a particular section, perpendicular to the bisector of the angle between the caustic lines, was chosen so that the general form of the illumination curve was practically the same as that obtained by calculation, and then the positions of the successive maxima with respect to the central line cc' (Fig. 5) were measured. The calculated and observed values are tabulated below for comparison, for the two cases for which values have been calculated.

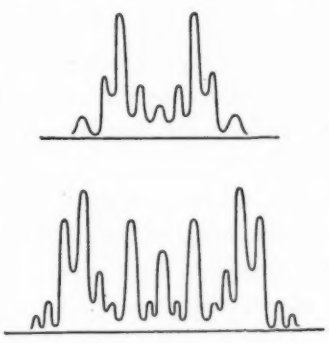

Fig. 6.

TABLE II.

Serial No. of Max. (Reckoned from the Central Direction).	Separation of Caustics 0° 56′.			1° 52′.		
	Calc. Intensity.	Position of Max.		Calc. Intensity of Max.	Position of Max.	
		Obsd.	Calc.		Obsd.	Calc.
1	1.6	0° 10′	0° 11′	0.5	0° 8′	0° 8′
2	4.0	0° 21′	0° 21′	1.7	0° 17′	0° 18′
3	2.0	0° 31′	0° 30′	0.4	0° 26′	0° 29′
4	0.7	0° 41′	0° 41′	0.9	0° 33′	0° 36′
5				2.2	0° 43′	0° 43′
6				1.7	0° 53′	0° 54′
7				0.5	1° 4′	1° 3′
8				0.3	1° 13′	1° 10′

(Radius of the cylinder = 0.0184 cm.; $\lambda = 5.5.10^{-5}$ cm.)

The agreement between the observed and calculated values is fairly close. It is also noteworthy that the maxima and minima seem to be ranged at roughly equal intervals.

Some explanation may now be given of the peculiarity of the phenomena, described in section (1), observed when the diameter of the

[1] The abscissæ are on the same scale in the two diagrams.

cylinder is very small. In a direction midway between the caustics, it may be noted that the rays emerging from points *a* and *c* (Fig. 5) have nearly equal paths, while the central ray from *b* differs very much in path from either of the other two. Hence we may regard the phenomena in white light as due simply to the superposition of a practically uniform illumination (due to the ray from *b*) on a fringe system due to interference of light from the two point sources *a* and *c*. It would be seen from Fig. 2 that the central fringes are very distinct and bright, and this would indicate that the effect due to the ray from *b* is much smaller than that due to those from *a* and *c*. This seems to be what actually happens, for, as a reference to Figs. 3 and 4 will show, there is in fact a greater concentration of the rays near the points *a* and *c* than at the center of the wave front. The achromatism of the caustics and their supernumeraries[1] is due to the fact that the effect of dispersion in the glass is compensated by that of diffraction of the emergent wave.

The work was carried out in the laboratory of the Indian Association for the Cultivation of Science. The writer wishes to acknowledge the interest taken in this investigation by Prof. C. V. Raman.

[1] See Mascart, Ann. de Chim. et de Phys. (6), 26 (1892).

THE EFFECTS OF GASES AND METALLIC VAPORS ON THE ELECTRICAL PROPERTIES EXHIBITED BY SELENIUM CRYSTALS OF THE HEXAGONAL SYSTEM.

By W. E. Tisdale.

THE photo-electric effect of certain crystals and metals has been observed to vary with the freshness of their surfaces, and with the different kinds of gas surrounding them.[1] It has also been suggested that perhaps the well-known action of light on selenium might also vary with the surface conditions, even though it is generally accepted that the change in selenium due to light is a volume, and not a surface effect.[2]

The following experiments were undertaken to ascertain what effect, if any, various vapors or gases would have on crystals of selenium. It was necessary to make crystals all under exactly similar conditions as to pressure, temperature, and rate of cooling upon removal from the incubator, in order to establish their uniformity. A set of eight tubes of selenium was evacuated at one time; sealed off separately, and placed in a Frease oven regulated for 185° C. Before sealing off the tubes, and while they were being evacuated, the selenium was boiled for about fifteen minutes to drive off all the gases in the stick selenium. The crystals were formed in sixty-nine days.

Of these eight tubes, three were picked at random for test crystals. The others were filled with the different gases and put aside that the crystals might soak in the various gases and come to a saturization point. The gases used were hydrogen, argon, nitrogen, oxygen and air. Air was taken as a standard for comparison. The vapors used were mercury. tin, bismuth, sulphur and arsenic.

The Effect of Gas on Selenium Crystals.

Before attempting to ascertain whether the gas in which the different crystals had soaked produced any change in their electrical properties, *i. e.*, their resistance, sensitiveness to light, maximum wave-length sensibility, rate of action under light, and rate of decrease of resistance upon removal of light stimulus, it was necessary to determine whether

[1] T. Wulf, Ann. der Physik, 9, pp. 946–963, 1902. Kunz and Stebbins, Phys. Rev., Vol. 7, p. 62, 1916.

[2] F. C. Brown and L. P. Seig, Phil. Mag., Vol. 28, p. 497, 1914.

crystals made under similar conditions acted alike when subjected to similar treatment after production.

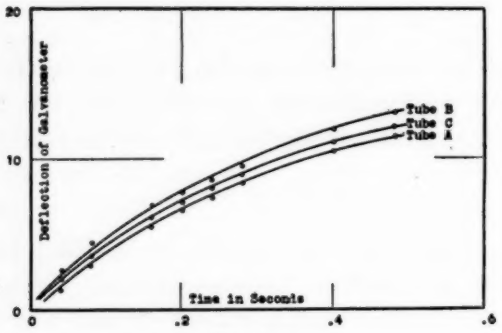

Fig. 1*a*.

For this point, crystals from various parts of each of the three test-tubes were selected, and their properties determined. The crystals chosen were taken as near the same size as was possible to select them without microscopic measurements. The mean specific resistance for the test crystals was found to be 8.5×10^5 ohms per sq. mm. In Fig. 1

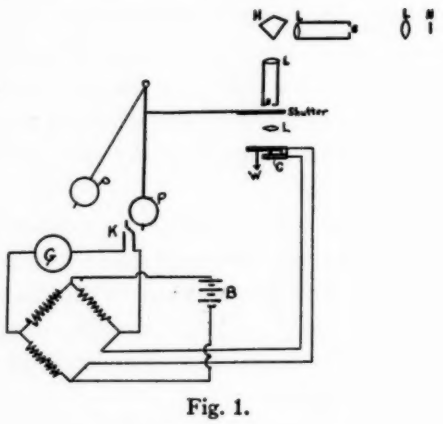

Fig. 1.

Action curve of test crystals.

is shown the action curves for these crystals. They were obtained by placing the crystals in the contacts shown at *C* in the diagram of apparatus, where the crystal was in the dark, and then subjected to the action of light for intervals varying from .04 second to .48 second, and measuring the resultant change in resistance. The change from equilibrium in the dark to that in the light was then plotted as a function of the time. It is seen that in general the slope of the curves are the same, indicating that the rate of decrease of resistance with time under given light condi-

tions is constant. For the recovery to normal dark conditions after being exposed to the light, a constant α was calculated from the theory of recovery proposed by Dr. F. C. Brown.[1]

This theory assumes a certain similarity between the theory for recombination of negative and positive electrons in gases and the recombinations of negative electrons and positive residues in selenium crystals. Rutherford[2] has shown that if in a gas n_1 negative and n_2 positive ions are present, the rate of recombination is directly proportional to $n_1 \times n_2$ expressed by the equation:

$$\frac{dN}{dt} = -\alpha(N_1 \times N_2),$$

where α is a constant called the coefficient of recombination. It assumes that for short intervals of time after the light has been cut off that the decrease in conductivity of a selenium crystal is due to the recombination of the conducting electrons with the positive residues, and that this recombination takes place according to the same law as that which holds for gases. If the number of electrons taking part in the conduction is proportional to the conductivity, the rate of recombination may be calculated from the equation:

$$\alpha = -\frac{dC}{C^2 dt},$$

where dC is the decrease in the conductivity during the time dt that the crystals have been in the dark; C is the equilibrium value of the conductivity in the light; and α is proportional to the coefficient of recombination. It is therefore necessary to assume:

1. When a crystal is in equilibrium in the light or in the dark the conductivity is proportional to the number of negative electrons taking part in the conduction.

2. Recombination takes place in selenium crystals according to the same law as in gases.

3. The rate of recombination in the light is the same as in the dark.

The constant α was measured for crystals from the tubes of test crystals, and were found to be for

tube A ..... 2.68×10^5,
tube B ..... 2.90×10^5,
tube C ..... 2.84×10^5.

These values are in very good agreement.

[1] PHYS. REV., Series 2, Vol. 5, p. 395, 1915.

[2] Phil. Mag., Ser. 5, vol. 44, p. 422, 1897, and Ser. 5, vol. 47, p. 109, 1899.

In Fig. 2 is shown a further similar relation between these crystals from the tubes of test crystals. These curves are a relation between

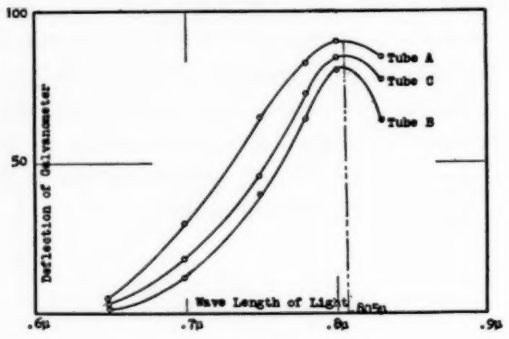

Fig. 2.

Wave-length sensibility curves of test crystals.

resistance and wave-length of incident light, and show what is known as wave-length sensibility relations.

They were obtained by placing the various crystals in the same position *C* in the apparatus diagram and subjecting them to the same spectrum, produced by a Hilger monochromatic illuminator, where this spectrum was not an equal energy spectrum for all wave-lengths, but was the same energy for all crystals at any given wave-length. The curves are of the same shape and show uniformly a maximum wave-length sensibility at a little further in the red end of the spectrum than .8 μ—roughly about .805 μ.

From the various tests here applied, it is justifiable to assume that the crystals in the entire set of tubes made at the same time under identical conditions of pressure, temperature, and rate of cooling, would show identical properties of resistance, light action, recovery from light, and wave-length sensibility if they were all treated alike after production. And further, that if any difference be detected after subjecting them to different treatment, that this treatment is the cause of the difference found. These crystals will therefore be assumed to be normal crystals made in vacuum and tested in air, and the various other crystals will be compared to them. The results will not be referred to absolute measurements, but will be entirely positive. Only one crystal from each tube will be used in the comparisons, but each one has been checked against many others selected at random from the same tube to be certain that it is not an isolated crystal.

In Fig. 3 is shown the action curves for the different crystals. They were obtained as were the corresponding curves for the test crystals,

but show a marked variation from the similarity noticed there. It will be observed that the crystals treated with nitrogen show a decidedly greater slope than any of the others, and the fact of a more rapid rate of

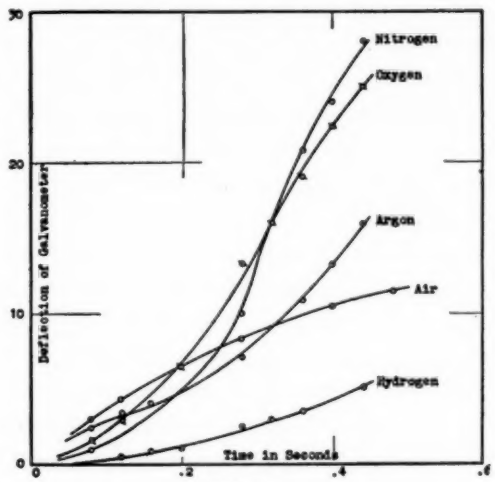

Fig. 3.

Action curves.

change of resistance with light stimulus, as these curves indicate, is very noticeable in working with the crystals. The hydrogen-treated crystals are the most sluggish over long periods of exposure, as well as for the short periods indicated in the curves. The air crystal is almost identical with those used as a standard.

Fig. 4 gives the rate of recovery data from which the coefficients of

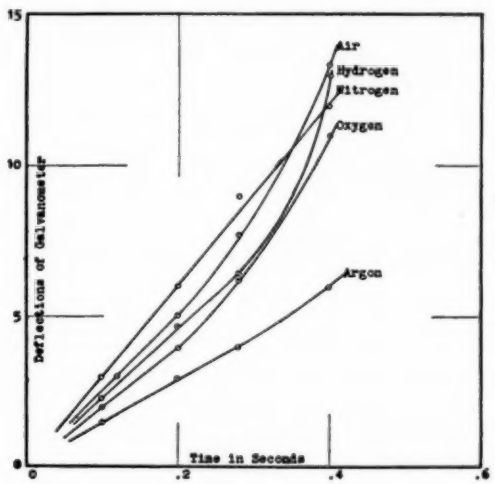

Fig. 4.

Recovery Curves.

recovery were computed. For short intervals of time the nitrogen-treated crystals again show a more marked rate of change than do the others. Argon crystals are very slow in their recovery after exposure to light.

The wave-length sensibility curves in Fig. 5 are particularly interesting. It is to be noticed that nitrogen crystals have changed at their maximum about fifty per cent. more than the comparison crystals changed. In white light, the nitrogen crystals changed their resistance so that the ratio of resistance in the light to that in the dark was 3.4, while the ratio for the comparison crystals was 3.2. Oxygen ratio was 2.8, hydrogen 3, and argon 2.5. These curves show that in monochromatic light the ratio of resistance change is of the same order—nitrogen showing the largest ratio, and the argon crystals the smallest.

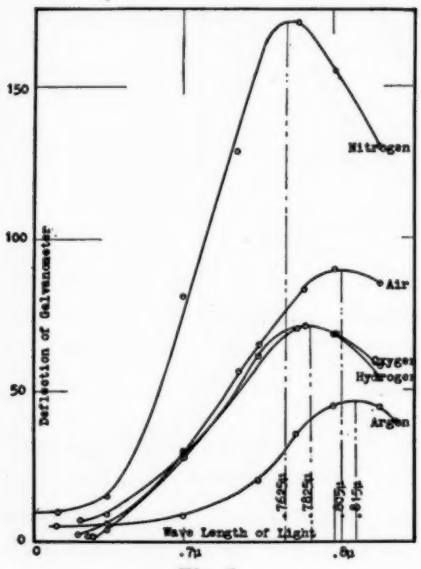

Fig. 5.

Wave-length sensibility curves.

These curves also show a decided difference in the wave-length at which the various crystals reach a maximum. The observations show decided maxima at the wave-lengths indicated. There seems to be no reason why these different maxima should show the law of progressive variation with the gases that the resistance and other effects show.

TABLE I.

	Wave-length Sensibility. (From Fig. 5)	α	$R_d \div R_L$	Specific Resistance.	Atomic Weight.
N.....	1	10.3×10^5	3.4	1.16×10^5	14
Air.....	2	2.68×10^5	3.2	8.5×10^5	
O.....	3	1.7×10^5	2.8	7.5×10^5	16
H.....	4	1.37×10^5	3	14.5×10^5	1
Ar.....	5	1.07×10^5	2.5	9.2×10^5	40

In Table I. is recapitulated the various facts observed. In the first column the crystals are arranged according to their amount of change in resistance at their maximum wave-length sensibility, as shown in Fig.

5. In the second column, values of α are shown, and in the third, the factor showing the ratio of their resistance in the light to that in the dark is given. The fourth column shows the specific resistance of the various crystals, but is subject to considerable error due to the smallness of the area of contact. It is to be noticed that the crystals showing the greatest change in resistance from light to dark also show the greatest coefficient of recombination, as indicated by α. They also show the greatest change at their most sensitive wave-length, and in general, the least specific resistance.

It seems that of these gases, nitrogen improves the action of the crystals far more than do any of the other gases, and that argon does the most damage. Now from the work of Kunz and Stebbins[1] and others, who have shown that argon is one of the most effective gases in photo-electric effects, it seems correct to conclude that there is no relation between photo-electric effects and light sensitiveness in selenium, as is shown also by F. C. Brown in some recent unpublished results.

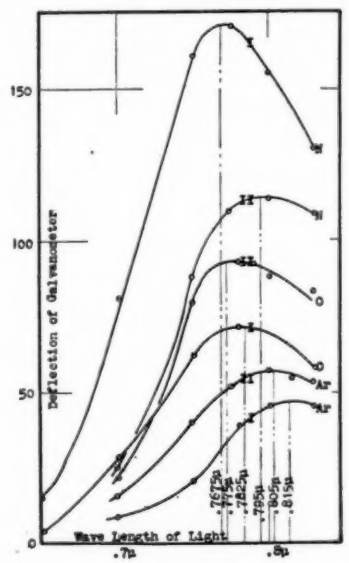

Fig. 6.

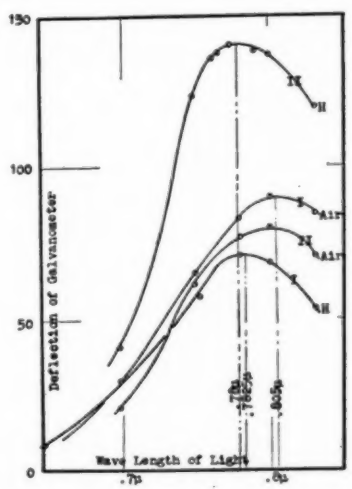

Fig. 7.

Wave-length sensibility curves of crystals taken from vacuum to gas to air.

Inasmuch as nitrogen appears to be the most helpful of these gases, the other gases seem also to be arranged in order naturally, because air containing four fifths nitrogen, about one fifth oxygen, and small parts of hydrogen and argon, should be next to nitrogen, and should be better than the others, as is shown to be the case. Also, oxygen should come

[1] PHYS. REV., p. 62, Vol. VII., 1916.

third, as it does. Hydrogen and argon follow in their order. Now arranged according to atomic weights, except for hydrogen, these gases also occur in order—the heavier gas being more detrimental than the lighter ones. Hydrogen may be peculiar in its action here as it is in its action on platinum.

After the various tests before given were made, the crystals were placed in separate glass containers, and allowed to stand in dry air ninety days, when they were again tested for maximum wave-length sensibility, and for the values of α. In Figs. 6 and 7 these last curves are compared with those shown in Fig. 5. The curves of Fig. 5 are marked *I* and those of the last tests are marked *II*, and are presented to show the different degrees of change in the differently treated crystals. It will be noticed that the crystal taken from the vacuum tube to air (Fig. 7), has changed but very little, either in sensitiveness or wave-length at which a maximum occurs. The hydrogen crystal has changed more than other—its change in conductivity is about 100 per cent., and its maximum now occurs at .7825 μ instead of .78 as formerly. The conductivity of the nitrogen crystal has been reduced by a factor of two thirds, and its maximum shifted from .7675 μ out to .795 μ. The oxygen and argon crystals have changed, as can be observed, but in less degree. The principal point for these two is the shift of the maximum (Fig. 6). The values of α shown in Table II. are of interest. These show, as do the curves in Fig. 8, a tendency towards the value of the crystals observed in air throughout the experiment. The recovery of argon has increased by nearly five times, and oxygen two times. Nitrogen has decreased to one third its former value, and air and hydrogen have remained nearly as before. In Fig. 8 the curves marked *II* in Figs. 6 and 7 are compared with each other to show the contrast with the same crystals shown in Fig. 5.

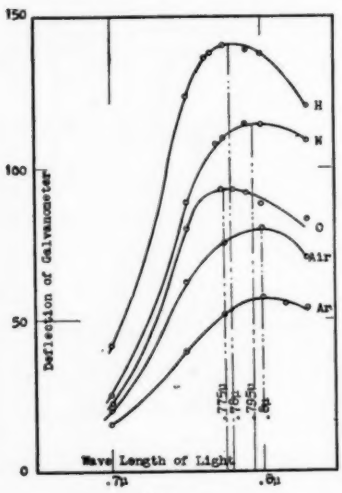

Fig. 8.

Wave-length sensibility curves.

TABLE II.

	After Soaking in Gas.	Ninety Days Later in Air.
N.....	10.3×10^5	3.05×10^5
Air.....	2.68×10^5	2.62×10^5
O.....	1.7×10^5	2.64×10^5
H.....	1.37×10^5	1.65×10^5
Ar.....	1.07×10^5	5.18×10^5

CRYSTALS MADE IN NITROGEN AND HYDROGEN.

At the same time that these previous crystals were made in vacuum tubes, selenium was crystallized in an atmsophere of nitrogen, and also of hydrogen. The results were different than for those made in vacuum and soaked in these gases, the reason being that the gas in the tube was at a pressure of nearly two atmospheres, which altered the temperature gradient as well as modifying the pressure under which the crystals formed. The maximum wave-length sensibility for crystals made in hydrogen was the same as for crystals made in vacuum and soaked in hydrogen—both occurring at approximately wave-length .785 μ. There were no remarkable properties of these crystals except that they were very slow of action, as were also those made in vacuum and soaked in hydrogen, requiring at least ten minutes to reach an approximate equilibrium value from dark to light, and requiring hours to recover approximate equilibrium from dark to light.

The crystals made in nitrogen furnished more interesting results. At times they would respond as do the normal crystals, that is, those that in response to light decrease their resistance by certain ratios, depending upon the time of exposure and the intensity of the light. At other times these same crystals would suddenly decrease their resistance while remaining in the dark, and upon exposure to light in this condition, would increase their resistance. There seemed to be no good explanation of these effects, but it had been previously observed that during the process of baking the crystals there had developed in this tube a small crack. The probability of effect by gases was dismissed, but the possibility of the entrance of metallic vapor from the heating coils of the oven suggested a series of experiments to determine their effect on selenium crystals.

THE EFFECT OF METALLIC VAPORS ON SELENIUM CRYSTALS.

A tube of selenium was prepared as previously described for making crystals, except a small tube filled with fillings of pure tin was put in the larger tube along with the selenium. There was no contact between the selenium and the tin except in the vapor state, both being at a temperature above the melting point of tin. Crystals formed without any visible difference in color, size or general appearance. Their resistance was of the same order of magnitude as for those prepared in the usual manner—about 2 to 3 $\times$ 10^5 ohms per millimeter cube. However, they were strikingly different from normal in that they were absolutely neutral to the action of light within the limits of the galvanometer which had a sensitiveness of 10^{-9} amperes. A 500-watt nitrogen-filled lamp at a

distance of 50 centimeters had no effect on the conductivity of any of these crystals.

When sulphur replaced the tin in the small inner tube, the crystals were exceedingly irregular, and very short and thick. In general they were decidedly grayish in color. Their resistance was several times as much as normal crystals, and their resistance change with light was of the same order as these vacuum-made crystals. Their maximum sensibility occurred at .83 μ, with very sluggish recovery and action rates. The remarkable fact about the experiment with sulphur was the number of red crystals produced. These red crystals were exceedingly small—too small for deffnite analysis—but when viewed through a microscope their angles could be definitely seen. When viewed through crossed Nichols they appeared a brilliant red, indicating a double refracting power —a character purely crystalline. When tested for conductivity, to the limits of the apparatus, they showed none. Red crystals of selenium produced by sublimation are particularly rare, having been, so far as known, obtained but once, and those by F. C. Brown.[1]

When bismuth replaced tin, there was no apparent deviation from the normal crystals.

Normal crystals made in vacuum and tested in air were placed in metallic vapors, and their resistance changes observed. The crystals were arranged so that they were not heated as the vapors were drawn over them by means of a pump. All the metallic vapors showed the same effects. If the vapor was drawn over them for too long a period, a thick coating deposited, and there was no other change in the crystal's apparent resistance than a decided lowering, due entirely to the conducting film of metal, and there was no light sensitiveness. If, however, a sufficiently thin layer were deposited by varying the time of exposure to the vapor, for small currents, the resistance would be very low—as for example a crystal whose dark resistance was 3.9×10^6 ohms, when placed in tin vapor for four hours, showed a resistance of 9.9×10^3 ohms. In its original state the crystal was light positive, but in the second state it was light negative. Its negative action was not steady, however. This result was typical of the action of the vapors of bismuth, arsenic and mercury.[2]

There is a possible explanation of this action. It is well known[3] that if a small V-shaped trough has a fine thread of mercury in the bottom, and a current be sent along it, there is a tendency for the mercury to form globules, which breaks the current. This tendency depends upon

[1] PHYS. REV., N. S., Vol. IV., No. 2, Aug., 1914, p. 85.

[2] F. C. Brown, PHYS. REV., N. S., Vol. II., No. 2, p. 153, Aug., 1918.

[3] E. F. Northrup, Metallurgical and Chem. Eng., Jan., 1913.

the size of the current and the size of the thread of mercury. Now with a very thin layer of the metal on the crystal, a small current which is shared by both the crystal and the thin layer will not cause the layer to ball up, but upon subjecting the combination to light, there is enough additional current permitted to flow by the action of the selenium to cause the layer to ball up and break the circuit through it, thus causing all the current to go through the crystal. This, in turn, due to the high resistance of the crystal, causes an apparent light-negative action, *i. e.*, an increase of resistance due to light, instead of the normal decrease. Such a continuous action would cause such fluctuations of the currents as are observed. If one of these crystals showing varying resistance features due to a layer of condensed metallic vapor be connected in the apparatus shown in the diagram of apparatus, and an electro-magnetic wave be sent through the room by the spark from an induction coil, the resistance will instantly increase to approximately its normal value, and for a particular one tested, it required ninety-six hours to again reach a low resistance, having remained undisturbed meanwhile. The action of the electro-magnetic wave is to send a very appreciable current through the layer (the circuit acting as an antenna), which breaks up the film to a larger extent than can occur under the action of light.

Summary.

1. It has been shown that selenium crystals of the hexagonal system show identical properties when they have been subjected to the same conditions during and subsequent to their production.

2. That their various light electrical properties may be altered by subjecting them to the action of different gases. Whether these gases, in a gas layer, change crystal stresses, or vary the energy received from a constant source is not determined.

3. That the effect of the gas seems to be more detrimental the higher the atomic weight of the gas.

4. That the effect of making crystals in gases is but little different than making crystals in vacuum, and subjecting them to gas.

5. That the effect of metallic vapors is to form a conducting film on the surface that may, under certain conditions, give an apparent light-negative action to crystals that are normally light positive.

NEW BOOKS.

Essentials of Physics. By DANIEL W. HERING. New York: D. Van Nostrand Company, 1918. Pp. ix + 367. Price, $1.75.

This work is the outgrowth of a course of lectures designed for students who do not intend to specialize in physics or engineering, and is, therefore, not so full of detail and mathematical applications as some other texts. It is intended that the outline thus presented should be expanded by the teacher and by the reading of references to other books. Thus supplemented, the book should be a very satisfactory text. A number of well-selected lecture experiments are described. Some points are open to criticism, for example the use of the expression "latent" heat, the description of the "ultragaseous" state of matter in Crookes' tubes, and the statements that the nature of the X-rays is not known and that radium emanation (not alpha particles) becomes helium. Doppler's principle is correctly stated for the case of a moving observer, but the same formula is then applied to the somewhat different case of a moving source. This error is frequently made in text-books.

E. P. L.

The Origin of our Planetary System. By EUGENE MILLER. Topeka, Kansas: Crane and Company, 1918. Pp. 1 + 90. Price, $.50.

The author advances the hypothesis that the sun and Jupiter formed originally a simple binary system, with orbit of great eccentricity. While Jupiter was still in a molten state, when it approached perihelion tidal action caused the detachment of masses of the matter on the side toward the sun, and the reaction was followed by a similar effect on the opposite side. Thus the inner and the outer planets were born. Smaller masses irregularly and explosively projected from Jupiter gave rise to comets, which would thus be associated with the larger outer planets formed at the same time. A consequence of the hypothesis is that two outer planets remain undiscovered. The relative sizes, densities, and orbital peculiarities of the planets are discussed from the standpoint of this hypothesis. The arguments may not be convincing to all readers, but the book is well written, and the writer displays a spirit of becoming modesty.

E. P. L.